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SIMULATING SUSTAINMENT FOR AN UNMANNED LOGISTICS SYSTEM CONCEPT OF OPERATION IN SUPPORT OF DISTRIBUTED OPERATIONS

by

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Marine Corps logistics always seeks to remain responsive, flexible, and sustainable to successfully support highly maneuverable units dispersed over large operational areas. The variety of Marine Corps battlespaces and the constant evolution of enemy weapons and tactics, however, makes logistic support increasingly difficult. Unmanned logistics systems (ULS) show potential to reduce Marine personnel risk and workload, and increase throughput, efficiency, and flexibility.

To assist in the development of ULS operational concept and platform employment, this thesis uses discrete event simulation and a designed experiment to model and explore a ship-to-shore logistics process supporting dispersed units via three types of ULSs, which vary primarily in size. Major findings from the analysis illustrate the importance of the type of logistics method used in predicting successful re-supply and risk effects to the system. The hub-and-spoke re-supply method is less variable, returns higher ratios of delivered supplies, and performs better independent of risk when compared to the linear method. The observed method affects increase with the distance a unit is from the main logistics node. Small ULSs should be used for just-in-time re-supply, medium ULSs should be used for throughput, and all systems should be survivable to minimize risk.

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ABSTRACT

Marine Corps logistics always seeks to remain responsive, flexible, and sustainable to successfully support highly maneuverable units dispersed over large operational areas. The variety of Marine Corps battlespaces and the constant evolution of enemy weapons and tactics, however, makes logistic support increasingly difficult. Unmanned logistics systems (ULS) show potential to reduce Marine personnel risk and workload, and increase throughput, efficiency, and flexibility.

To assist in the development of ULS operational concept and platform employment, this thesis uses discrete event simulation and a designed experiment to model and explore a ship-to-shore logistics process supporting dispersed units via three types of ULSs, which vary primarily in size. Major findings from the analysis illustrate the importance of the type of logistics method used in predicting successful re-supply and risk effects to the system. The hub-and-spoke re-supply method is less variable, returns higher ratios of delivered supplies, and performs better independent of risk when compared to the linear method. The observed method affects increase with the distance a unit is from the main logistics node. Small ULSs should be used for just-in-time re-supply, medium ULSs should be used for throughput, and all systems should be survivable to minimize risk.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	Air Combat Element
APOD	aerial points of debarkation
BLT	Battalion Landing Team
BN	battalion
C2	command and control
CAB	Capabilities Assessment Branch
CE	Command Element
CLR	combat logistics regiment
CMC	Commandant of the Marine Corps
CO	company
CONEPS	concept of employment
CONOPS	concept of operations
CP	command post
CUAS	cargo unmanned aircraft system
DES	discrete event simulation
DOA	days of ammunition
DOE	design of experiments
DOS	days of supply
FOB	forward operating base
GCE	Ground Combat Element
I&L	Marine Corps Installations and Logistics
IOH	inventory on hand
LCE	Logistics Combat Element
LSA	logistics support area
MAGTF	Marine Air-Ground Task Force
MCWL	Marine Corps Warfighting Lab
MEU	Marine Expeditionary Unit
MOC	Marine Corps Operating Concept
MRE	Meals-Ready-to-Eat

MUM-T	manned-unmanned teaming
NOB	nearly orthogonal and balanced designs
NPS	Naval Postgraduate School
OAD	Operations Analysis Directorate
OEF	Operation Enduring Freedom
PAX	personnel
PLT	platoon
Ptrl	patrol
RAS	robotic autonomous systems
ROP	re-order point
SEA	sea-base
SPOD	sea port of debarkation
TOC	tactical operations center
UAS	unmanned aerial system
ULS	unmanned logistics system
USMC	United States Marine Corps

EXECUTIVE SUMMARY

To support highly maneuverable units dispersed over large operational areas, Marine Corps logistics support systems must be responsive, flexible, and sustainable. These goals can be difficult to achieve in light of the wide variety of battlespaces in which the Marine Corps must operate and the constant evolution of enemy weapons and tactics. The use of unmanned systems could reduce Marine personnel risk and workload, while increasing throughput, efficiency, and flexibility in logistics processes. No doctrinal concept of operations or concept of employment currently exists, however, for Unmanned Logistics System (ULS) sustainment.

This research combines simulation, designed experiments, and data analysis to gain insight into how ULSs can be leveraged to logistically support dispersed small units, ultimately informing operational concepts and platform employment. A discrete event simulation models the logistics chain from seabase to small level unit (i.e., platoon level). Inputs to this simulation include, but are not limited to: ULS speed and payload, distances between units, initial days of supply, number of ULS per unit, system risk, and logistic method of re-supply. The designed experiment enables ranges of inputs to be run in the simulation so that significant input factors are illuminated and to display trends in the logistics process. Using tools such as partition trees, regressions, and box plots, the simulation output is analyzed and the major findings are as follows:

- Out of the factors that can be controlled, ULS employment method is more important than ULS specifications, number of systems, or any other factor, in predicting successful re-supply. The hub-and-spoke method demonstrates less variability across most design points, returns higher ratios of successfully delivered supplies, and performs better at both high and low risk than the linear method of distribution.

- The number of medium and large ULSs are important factors for most of the Marine units, while the specific ULS specification factors (e.g., payload, speed) are much less important. This implies that the quantity of ULS employed matters more than the ULS capability specifications. From an acquisitions perspective, this result illustrates that having a “70% solution” for a ULS platform is good enough. The system does not have to be comprised of an exacting set of specifications because overall, achieving the perfect set of specifications has a limited effect on the

effectiveness of the ULS re-supply system. Developing a cost-effective and “good enough” ULS that could be procured in large quantities, and employed extensively, would have a larger effect on the efficiency of conducting distributed logistics operations than would the development of the perfect ULS.

- The farther a unit is from the main logistics node, the greater the effect of the re-supply method on high ratios of re-supply. If the platoon is the farthest entity away from the main units and is the “most important” by virtue of being the first to engage the enemy, employment of the hub-and spoke method rather than the linear method, benefits them the most.

- Small ULSs (S-ULSs) should be utilized for just-in-time logistics (i.e., rapid delivery of small loads), because S-ULS numbers did not appear as an important factor, other than at the platoon level. (The S-ULS was only significant at the platoon level because the company resupplied the platoon only via S-ULSs when operating based on the linear method.) Because of their relative unimportance in the overall supply ratios for units, they should not be used for throughput operations. If the S-ULSs merely fulfills a just-in-time mission, there is not a large procurement requirement for the system.

- In contrast to the S-ULS, the quantity of medium ULS (M-ULS) employed was a significant factor at nearly every Marine unit level and therefore should be used for throughput functions (given the availability of small and larger ULSs, M-ULS are preferred). The M-ULS size should be the primary focus when conducting ULS throughput operations.

- The logistics process is inherently complicated and chaotic. This makes it hard to control and even harder to predict. Variability within the system, however, can be mitigated. Risk is a significant factor in the simulation, and this analysis shows that the mitigation of this risk is a large predictor of re-supply success. Employing a survivable and reliable system is important in mitigating this risk.

- While this research did not consider command and control systems, in order to have sustainment visibility at all levels, the logistician would need to leverage a robust command and control architecture to effectively employ ULS re-supply systems.

- The methods used in this study can serve as a template for future work. Modeling a logistics process with different re-supply transportation is a cheap and easy way to gain insight about a system. While this research concentrated more on overall system processes, it would be advantageous to also look at more detailed information. Once a ULS has been procured, this model could be re-run with those ULS specifications.

Future work regarding ULS employment and operation could build on this framework in several ways, including continuing simulation work with the specifications of a Marine Corps procured ULS or the addition of scenarios, units, re-supply methods, and transportations types to the model. A user-friendly interface could turn this simulation into a planning tool that optimizes logistics re-supply using all assets available (i.e., ground transportation, air assets, and ULSs) or as an analysis of Marine Corps assets that could be replaced in favor of the ULS. Finally, the model could be expanded to future simulation experiments to assist in the design of a command and control infrastructure that meets the requirements of a ULS re-supply process.

Marine Corps logistics serves the warfighter, and its processes need to be flexible and sustainable enough to support dispersed and varied combat operations. While the Marine Corps is currently performing logistics without the ULS, the addition of this adaptive technology to the logistician’s arsenal will add process flexibility, reduce risk, and help modernize the force. Whether this asset is employed to keep re-supply trucks off improvised explosive device-laden roads, free air assets to perform missions other than delivery, or act as a ship-to-shore connector, this simulation and analysis show that ULSs are a capability that enable efficient logistics throughput and ultimately increase combat power.

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> And he has never given up his conviction that if you just try all the doors one of them is bound to be the Door into Summer. You know, I think he is right.
>
> —Robert A. Heinlein

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I. BACKGROUND

A. INTRODUCTION

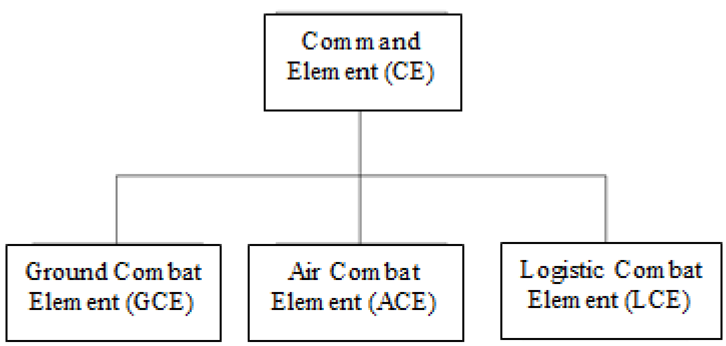
To support highly maneuverable units, dispersed over large operational areas, Marine Corps logistics support systems must be responsive, flexible, and sustainable. These goals can be difficult to achieve in light of the wide variety of battlespaces in which the Marine Corps must operate and the constant evolution of enemy weapons and tactics. Employment of unmanned systems has the potential to reduce Marine personnel risk and workload, while increasing throughput, efficiency, and flexibility in logistics processes. However, no doctrinal concept of operation or concept of employment currently exists for Unmanned Logistics System (ULS) sustainment. For the purposes of this thesis and in relation to the Marine Corps, ULS is the current terminology used to describe an unmanned aerial platform used for the delivery of supplies. This thesis focuses on general ULS capabilities rather than the capabilities of any specific system, but to keep in line with current Marine Corps studies, defines the systems in three different sizes based on capability. To aid in the development of how to employ this operationally necessary asset, a discrete event simulation models the logistics chain from seabase to small level unit (i.e., platoon level), ultimately informing the concept of operation and concept of employment of ULSs. This research triangulates simulation, data analysis, and logistical modeling to gain insight into how ULSs can be leveraged to logistically support dispersed small units.

B. BACKGROUND

To put the Marine Corps logistics model in context, Marine Corps organizational concepts must first be understood. This includes the arrangement of the Marine Air-Ground Task Force (MAGTF), and operational logistics as it pertains to supporting the MAGTF. The changing demands of the force and current studies related to ULSs within the Marine Corps will also be discussed. This chapter will conclude with the research question to be addressed and discussion of the research methodology.

1. Marine Corps Organization

The United States Marine Corps (USMC) takes pride in being an adaptable, forward-thinking organization, capable of readily and rapidly accomplishing a range of unpredictable missions. As 2ndLt Richard Kennard explained regarding his time on Peleliu during World War II, “My only answer as to why the Marines get the tough jobs is because the average Leatherneck is a better fighter. He has far more guts, courage, and better officers” (Johnson 2011). These “jobs” span from major combat operations involving kinetic ground forces, to saving lives and alleviating human suffering during crisis response. These missions are regularly expeditionary in nature and require support from the United States Navy, which has the ability to project from the sea. This type of mission is often termed an amphibious operation, which is doctrinally defined as a “military operation launched from the sea by an amphibious force to conduct landing force operations” (J-3 2014). To accomplish its range of missions, especially amphibious operations, the Marine Corps organizes as a MAGTF. Figure 1 is a visual representation of the basic MAGTF structure.



This composition can be scaled to support a range of mission requirements, and may contain a variety of supporting units.

Figure 1. Visual Representation of the MAGTF’s Basic Composition. Adapted from Headquarters, Marine Corps Combat Development Command (MCCDC) (1998).

As seen in Figure 1, the MAGTF is organized into four parts: the Command Element (CE), the Ground Combat Element (GCE), the Logistics Combat Element

(LCE), and the Air Combat Element (ACE). The CE is the headquarters of the MAGTF, and its function as the command and control center of the MAGTF is fulfilled by Marines organized into operations, intelligence, logistics, and administrative shops. The GCE is the heart of the MAGTF in its conduct of ground combat. It contains such units as infantry, artillery, tanks, and engineers. The LCE logistically supports the MAGTF in order to extend and sustain operational reach. Among other functions, the LCE provides supply, maintenance, transportation, and health service units. The ACE contains air assets that are used for a wide range of aerial missions, from assault support to reconnaissance. These four components of the MAGTF work in concert in pursuit of the overall MAGTF mission. As the component of the MAGTF that stands to gain the most in efficiency and effectiveness via the implementation of ULS, the LCE is the focus of this research.

2. Marine Corps Logistics

Logistics for the Marine Corps is often simply described as "beans, bullets, and Band-Aids," and supports every level of war (i.e., tactical, operational, and strategic). The emphasis of this thesis lies at the tactical level, due to the scope of the logistics model and the focus on dispersed small unit resupply in support of a military mission. The model depicts the tactical level because it concentrates on methods of support to units that are engaged in achieving a military objective (MCCDC 2011). At the tactical level, the core capabilities required to provide "beans, bullets, and Band-Aids" to a military mission include:

> Supply and maintenance systems to provide materiel readiness, transportation systems to effect distribution, services, general engineering, health services, and tactical-level command and control which links operation plans and the resulting logistic requirement to logistics capabilities and response. (MCCDC 1997)

To be effective, logisticians can either actively "push" scheduled resources to supported units, already knowing their requirements, or supporting units can request resources, "pulling" from logisticians based on consumption rates (MCCDC 1997). In this balance, logistics becomes both an art and a science that enables the application of combat power. Within this range of tasks, a logistician's ultimate priority is to give the commander flexibility while supporting mission goals and the operational scheme of maneuver (MCCDC 1999).

While all functional areas of logistics (supply, maintenance, transportation, general engineering, health services, and services) support the MAGTF, supply is directly consumed by supported units. This research focuses primarily on the provision of Class I and Class V, as no force, be it MAGTF or squad, will be able to leverage combat power without them. Class I is subsistence. This includes rations, both food and water, and takes the form of everything from Meals-Ready-to-Eat (MREs) to contracted provisions. Class V is ammunition in all its many forms, from bullets for a rifle to missiles and rockets. Without Class I, a force will starve, and without Class V, it will be combat ineffective.

In the performance of their duties providing the function of logistics, logisticians are guided by seven principles. They are responsiveness, simplicity, flexibility, economy, attainability, sustainability, and survivability (MCCDC 1999). When supporting distributed and highly maneuverable forces in a disputed area, however, responsiveness, flexibility, and sustainability become paramount.

Responsiveness "is the right support in the right place at the right time" (MCCDC 1999). Chief among the guiding principles, responsiveness demands that logistical efforts be tailored to support the tactical commander and the operation. Flexibility is "the ability to adapt logistics structure and procedures to changing situations, missions, and concepts of operation" (MCCDC 1999). When requirements change on the battlefield, flexibility allows for the execution of a successful response. This principle is only effective if there is centralized logistics control and decentralized action. Finally, logistics support for dispersed operations must be sustainable. Successfully sustained logistics means that, wherever they are, all customers receive constant logistic support throughout the operation MCCDC 1999). Long-term support is difficult, but operational reach can only be maintained by effective long-term logistical sustainment.

To maintain increasingly responsive, flexible, and sustainable logistics support in a complex and variable battlespace, logisticians must increasingly innovate. Emerging technologies, particularly ULSs, have the potential to be relevant and necessary tools that can increase throughput in support of the warfighter. This need for adaptive logistics and innovation has been discussed by the highest levels of the Marine Corps for the past decade.

3. The Commandant's Vision

The Commandant of the Marine Corps (CMC) is the Corps' most senior Marine who is responsible for organizing, training, and equipping the force. Several past CMCs, as well as the current CMC, have periodically released guidance focused on broad Marine Corps objectives. In 2007, then CMC General James Conway specified that the Marine Corps must modernize and streamline processes and capabilities. He also iterated the need for continued innovation in support of these efforts, specifically mentioning an "unmanned cargo delivery system" (Conway 2007). In 2014, General James Amos dictated that the Marine Corps must be "the right force in the right place at the right time" and re-focused the Marine Corps on its expeditionary nature through increased naval integration, development of seabasing operations, and compositing of forces. He stated that right force scaling can only be accomplished through reducing the "logistics footprint ashore" (Amos 2014).

In 2016, the current CMC, General Robert Neller, released the "Marine Corps Operating Concept" (MOC). Unifying the ideas of Generals Conway and Amos, General Neller's concept focuses on a modern expeditionary force (Neller 2016). To function as a modern force that is able to successfully project power from the sea, he wrote that the Marine Corps must adapt its structure and processes to contend with the changing threat of "complex terrain…[and] technology proliferation" (Neller 2016). In terms of logistics, this means that logisticians must sustain and support a distributed, highly maneuverable force in a contested area, and that leveraging unmanned systems and automation has the potential to transform and modernize the force (Neller 2016). Adapting to changes in the operating environment through the use of automation is a priority for the CMC.

The goal for the past decade has been the development of a modern expeditionary force, accompanied by an adaptable and sustainable logistics force. As strategic requirements dictate the conduct of increasingly distributed operations in more complex terrain supported by more flexible logistics systems, new technology could prove instrumental in achieving this goal.

4. Unmanned Logistics Systems

Although ULSs have been recently discussed by leadership with increasing regularity as a focus of developing technologies, they also have an operational and research history. ULSs had limited use in Afghanistan during Operation Enduring Freedom (OEF) and the research conducted based on these operations illustrates the value of the system in terms of reducing cost and risk, and increasing responsiveness.

In 1999, the first variation of the Kaman K-MAX unmanned autonomous system (UAS) was developed by Lockheed Martin and Kaman Aerospace Corporation as an adjustment to the Kaman K-1200 helicopter (IHS Jane’s Markit 2016). After a decade of research, testing, and contract development with the Marine Corps, two K-MAXs were deployed to Helmand Providence, Afghanistan, as the “first unmanned helicopter delivery operation in history” (Kaman K-MAX 2016). The deployed K-MAX can be seen in Figure 2. From December 2011 to May 2012, these systems moved more than 1.35 million pounds of cargo between main and forward operating bases (Kaman K-MAX 2016). The K-MAX UAS detachment continued operating until July 2014 after moving 4.5 million pounds of cargo supporting thousands of missions (Kaman K-MAX 2016). Capable of carrying a maximum cargo of 5,998 pounds and with speeds up to 115 miles per hour, the K-MAX proved capable in the real-world test of OEF.

Figure 2. An Unmanned, USMC K-MAX Operating in Helmand, Afghanistan. Source: Kaman K-MAX (2016).

5. Literature Review

The deployment of the K-MAX to Afghanistan resulted in real-world testing and data collection, which is enhanced when considered in conjunction with other research from the same time. A "Logistical Risk Planning Tool" that minimized risk in logistical support missions was created as research for a Naval Postgraduate School thesis (Merkle 2010). The tool optimized "the employment of logistical transportation vehicles comprising Cargo Unmanned Aircraft Systems (CUAS), ground vehicles, manned aviation platforms and the Joint Precision Airdrop System" (Merkle 2010). The study concluded that, given current capabilities, the CUAS were most effective when employed at the tactical platoon level, and that cargo capacity and speed were the most important factors for successful CUAS missions (Merkle 2010).

It was later determined that the Unmanned Aircraft System (UAS) would be an "attractive method to current methods of re-supply" (Peterson and Staley 2011). By analyzing K-MAX utilization versus standard ground and air logistics transportation during OEF, the study concluded that the UAS would decrease the need for ground logistics transportation, ultimately saving human lives (Peterson and Staley 2011).

One of the most extensive program of record studies for CUASs specifically looked at the K-MAX system as of 2013. This study identified the following benefits to procuring the CUAS: life cycle cost reduction, risk reduction, seabasing and MAGTF weight reduction, efficiency and responsiveness increases, and changes to the operating force requirements (Heffern et al. 2013). This study illustrated the overall benefit for CUASs in the Marine Corps.

As evidenced by these studies, the emerging technology of increasingly reliable unmanned systems are of obvious import because their application could reduce risk and workload, and increase throughput, efficiency, and flexibility in processes across the Marine Corps, both inside and outside the LCE. But before these systems can be organizationally implemented, their uses must be refined and thoroughly validated. General Neller acknowledges this constraint when he dictates that concepts must be refined concerning “manned-unmanned teaming (MUM-T), to integrate robotic autonomous systems (RAS) with manned platforms and Marines” and that a concept of operation (CONOPs) must be developed “that support and embrace RAS as a critical enabler” (Neller 2016). This prompted units within the Marine Corps to begin looking at a concepts of employment and operations for these systems.

More recently, in October of 2016, the Marine Corps Warfighting Lab (MCWL), in combination with Marine Corps Installations and Logistics (I&L), conducted a wargame to determine the concept of employment and concept of operation for three types of ULSs at various units within the MAGTF. The wargame focused on a scenario involving a Marine Expeditionary Force and the logistical support it would need for sustained operations. The movement of supplies occurred from seabase to units on the ground via small, medium, and large ULSs.

The final report from this wargame included recommendations for future ULS capabilities, numbers of ULS and locations, and the method by which the logistics element should provide direct support to enhance effectiveness (Marine Corps Warfighting Lab [MCWL] 2016). The report also concluded that ULSs were most effective in delivering emergency resupplies, rather than supplying throughput, that the application of ULS reduced the use of ground convoys and manned air assets, and were most useful in “high-risk environments” to reduce risk to assets and lives (MCWL 2016). These conclusions, however, were drawn from a seminar-style wargame; additional quantitative analysis is necessary to validate, modify, or refute these recommendations. Ultimately, the combined body of work will affect Marine Corps ULS procurement decisions.

C. RESEARCH QUESTION

Informed by past work on ULSs, as well as the recommendations made by the MCWL wargame, this analysis will address:

How can ULSs be employed to support flexible logistics sustainment on a distributed battlefield?

By using simulation, data analysis, and logistical modeling, this research attempts to inform ULS concepts of operation and employment.

D. METHODOLOGY

Logistical modeling, simulation, and data analysis are used to address this research question. A scenario based on the MCWL wargame is the basis of this model. It focuses on the logistics chain from seabase to a platoon-sized unit, dispersed from its company, and uses small, medium, and large ULSs to move supplies between units. This scenario is modeled using a discrete event simulation (DES). In order to more fully use the model’s capabilities, a design of experiments (DOE) approach runs the simulation across a wide variety of configurations drawn from ranges of input variables. Analyzing the data resulting from the DOE allows for the identification of important variables and interactions of variables, as well as other insights.

While Chapter I deals with the background and motivation for this research, Chapter II details the scenario and model. Chapter III focuses on the design of experiment, including the input variables. Chapter IV describes the analysis of results and findings, and Chapter V summarizes these findings with recommendations for the future employment of the ULS.

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II. SCENARIO

This chapter discusses the development and assumptions of the scenario used to simulate possibilities for ULS employment and operations in support of distributed logistics sustainment. The scenario is a simplified version of a ship to shore logistics process, and is predominately based on the MCWL wargame conducted in November 2016. Some of the modeling assumptions arose from other analyses completed in concert with the MCWL study, and will be addressed later in the chapter.

A. MCWL SCENARIO

The MCWL wargame is the primary basis for the thesis scenario and model. Therefore, in order to understand the simulation, the parameters and assumptions of the MWCL wargame must first be discussed. The MCWL wargame considers a Marine Expeditionary Unit (MEU), the smallest version of the MAGTF, positioned to conduct "expeditionary combat operations against a low to medium threat adversary," such as an amphibious landing in a country of interest, follow on combat operations, and logistics support from ships at sea to ground units (MCWL 2016). The scenario primarily focuses on the GCE and LCE, and the provisions of sustainment via small, medium, and large ULSs.

1. Mission

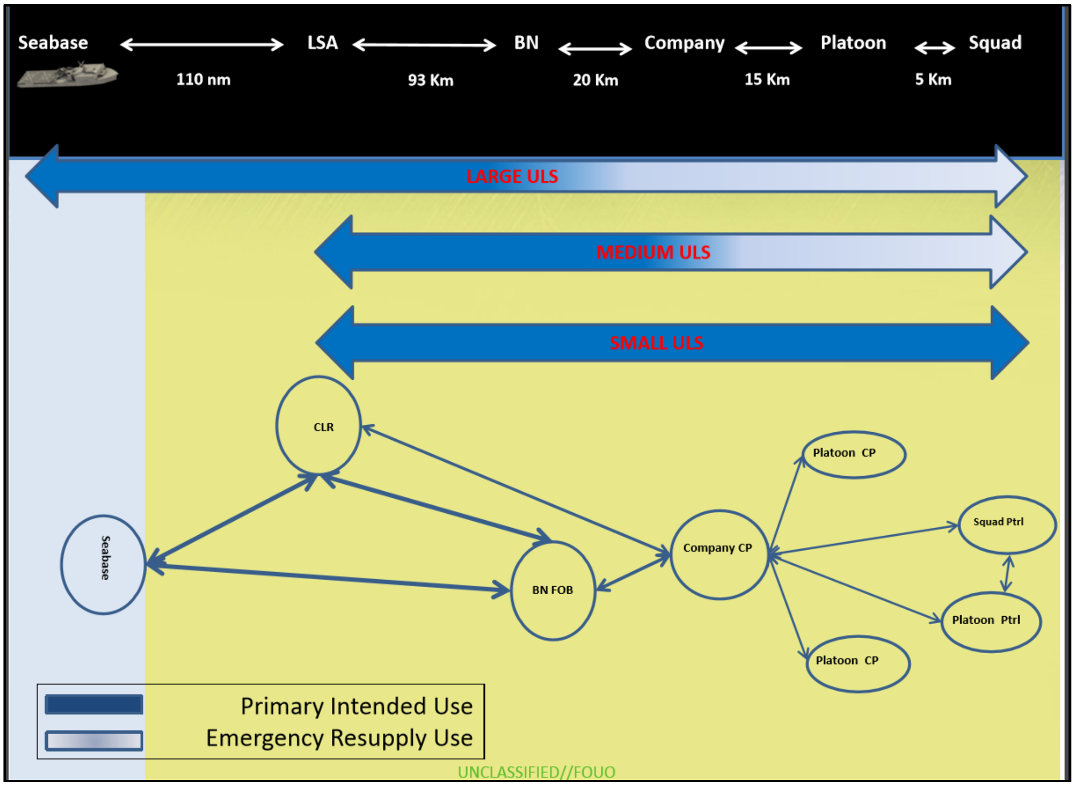
The proposed mission in the MCWL scenario considers operations conducted to counter enemy aggression. These operations support a local friendly government and its territories, and the defeat of enemy forces and the preservation of the local friendly government is the desired end state. To effectively defeat enemy combatants, however, ground units must be logistically supported. This thesis focuses on the logistical support system for ground units in this scenario, and the use of ULSs to sustain these ground troops while they perform their mission.

2. Concept of Operations

The concept of operations for the scenario describes the change in focus throughout the wargame in pursuit of mission success. For purposes of this thesis, the phases are named based on a joint military convention. Based on the 2016 MCWL wargame, the phases include:

- **Phase I (Shape)**: details the establishment of command and control (C2), preparation for the amphibious landing is conducted by coordinating with special-forces units and friendly local forces. After gaining air and sea control, the Amphibious Advance Force Operations can occur.
- **Phase II (Seize Initiative)**: friendly forces maintain sea and air superiority and secure the aerial points of debarkation (APODs) and sea port of debarkation (SPOD) in order to flow units and supplies into the country.
- **Phase III (Dominate)**: "sustained operations ashore" are conducted, enemy aggression defeated.
- **Phase IV (Stabilize):** C2 of the area is transferred to the United Nations.
- **Phase V (Enable)**: units are re-deployed.

These phases describe the preparation and landing of an amphibious force, and the follow-on combat actions that occur once the landing operations succeed. Although logistics sustainment is required in all phases, this research focuses on the sustained operations that typically occur in Phase III, in an effort to defeat the enemy. Logistical support can be effectively modeled for this point in operations, as units have landed and pushed into the country, forming a distributed network of mainly static units. This distributed network is what must be logistically supported. The static nature of this phase reduces the complexity inherent to developing a model for support of mobile units, while still providing an effective framework for assessing ULS capabilities in a distributed environment. Figure 3 is an example of the MEU's distributed combat operations; support originates from the seabase and travels inland to various units via various logistics platforms. The simulation used for this thesis exemplifies this concept of providing support from the sea.

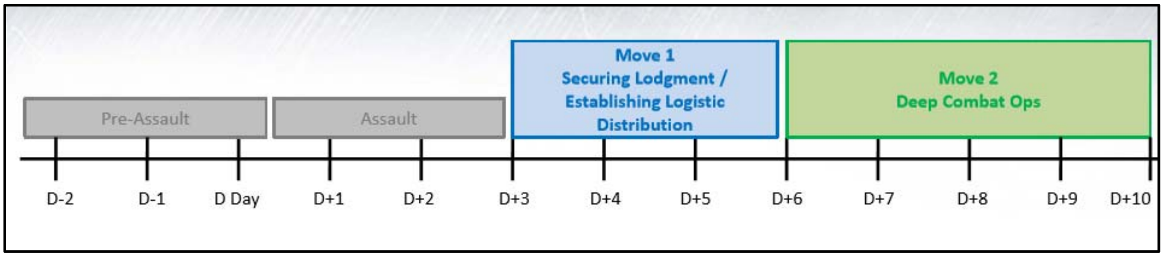


This example shows the distributed nature of amphibious operations and the need for a flexible and redundant logistics sustainment systems.

Figure 3. MEU Distributed Operations. Source: MCWL (2016).

For clarity, the units in Figure 3 will be referred to as their respective elements of the MAGTF. The CLR, or Combat Logistics Regiment, takes the role of the LCE. The BN FOB, or Battalion Forward Operating Base, serves the function of GCE Headquarters, and the Company and Platoon CPs and Ptrls are the unit's command post and patrols, respectively.

The events in the operation occur sequentially in time. Figure 4 shows the MEU's progression in pursuit of their mission and highlights the length of time that the MEU must be logistically supported.

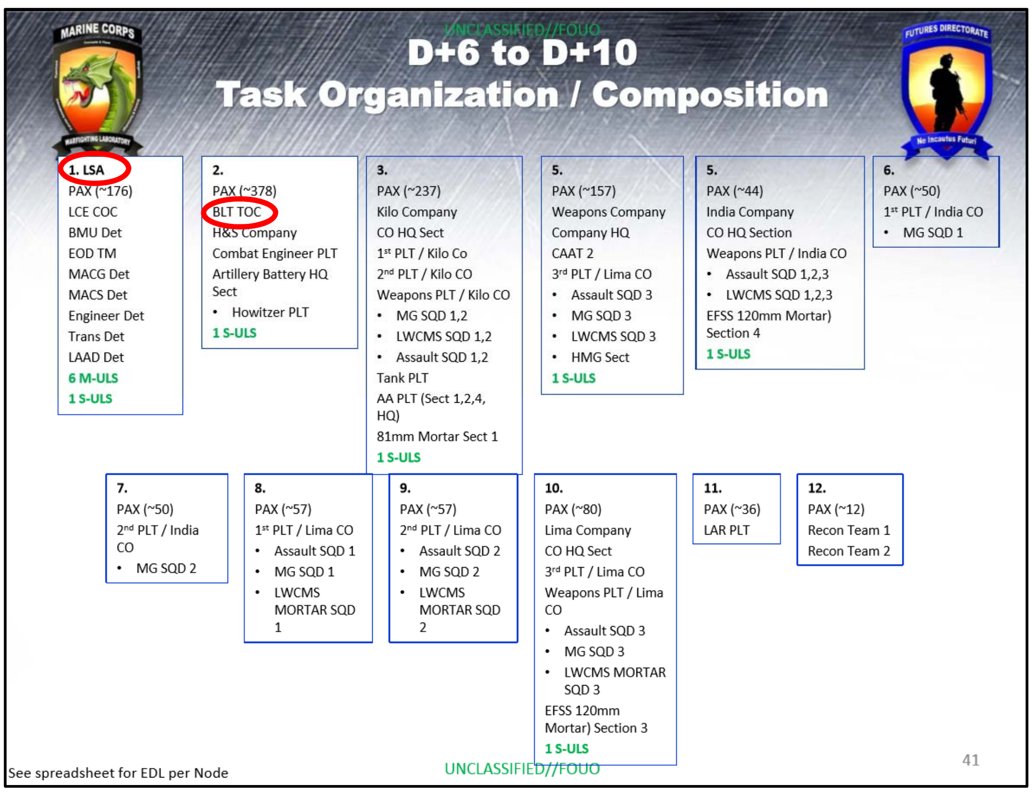


This timeline illustrates the lengths of various aspects of the simulated amphibious assault and the length of required logistic support.

Figure 4. MEU Operation Timeline. Source: MCWL (2016).

3. Units and Task Organization

Figure 5 illustrates the unit composition and organization for the MCWL wargame. The simulation for this thesis largely reflects this task organization, with a few differences that will be described in Section C.



The units involved in the MCWL wargame are various sizes and perform different functions in support of the overall mission.

Figure 5. Units in MCWL Wargame. Adapted from MCWL (2016).

In Figure 5, the LSA is the logistical support area and is operated by the LCE. The BLT TOC, or Battalion Landing Team Tactical Operations Center, is the equivalent of the GCE HQ, and the rest of the companies and platoons fill out the GCE's dispersed ground troops.

Each unit in the scenario is assigned a mandated amount of supplies to be carried. Days of supply (DOS) equals the amount of daily food and water that is required by a Marine or Marine unit. Days of Ammunition (DOA) can also be used as a metric for ammunition requirements. Figure 6 illustrates the MCWL wargame DOS considerations.

Other Considerations:
- 2 DOS at LSA
- 2 DOS at BN
- 1 DOS at CO
- 1 DOS at PLT
- Refueling Options
- SPOD/LSA supplies

Flexible and responsive logistics must be maintained to support units that commence operations with only one day of supply.

Figure 6. MCWL Wargame DOS Considerations. Adapted from MCWL (2016).

4. ULSs

ULS logistic resupply is the main focus of the MCWL wargame. The wargame divides ULSs into small, medium, and large varieties, each with unique system specifications. While the Marine Corps has yet to finalize ULS capability specifications for purposes of procurement, the MCWL wargame used the theoretical specifications detailed in Table 1.

Table 1. The ULS Specifications from the MCWL Wargame. Adapted from MCWL (2016).

Size | Spec	Payload (lbs)	Speed (kms/hr)	Endurance (hr)	Fuel Consumption (gal/hr)
Small	50	65	0.5	2
Medium	500	130	2	9
Large	5000	463	3.5	250

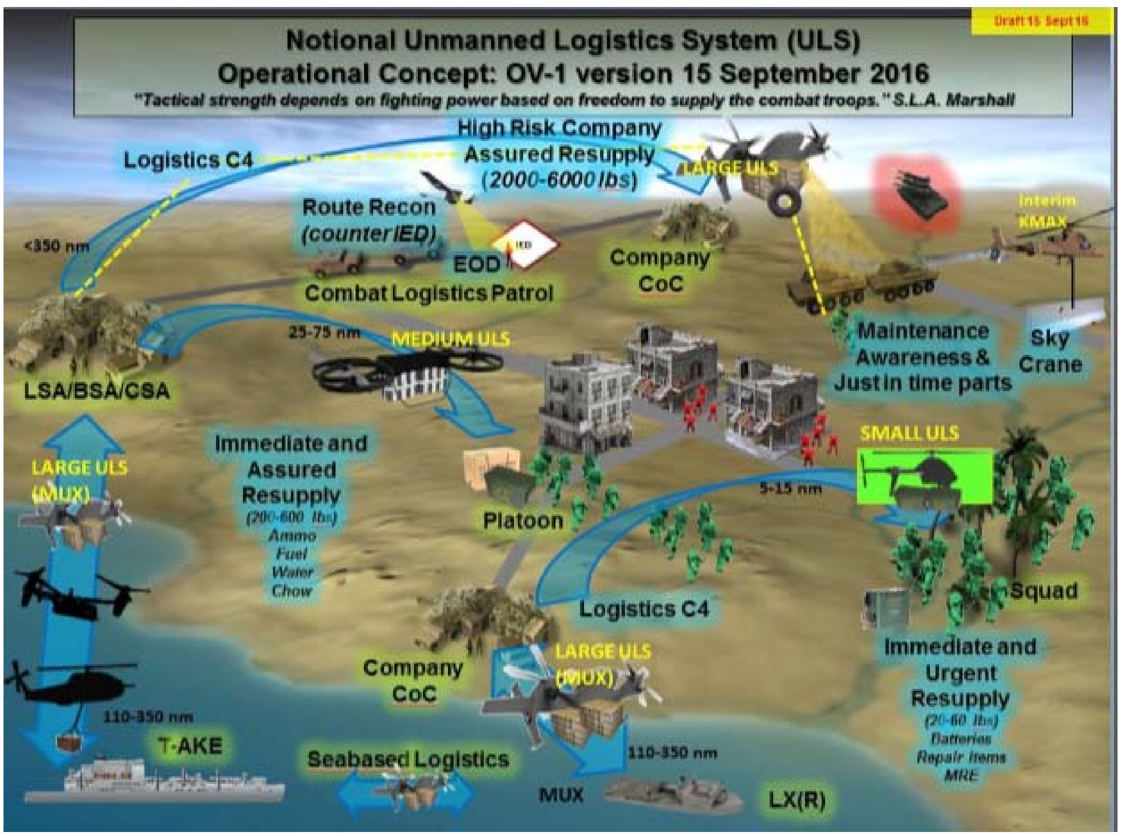
The scenario initially used a total of 14 ULSs, but the allocation was revised upon the scenario's conclusion to 20 ULSs. MCWL players initially allocated two large ULSs to the ACE for transporting supplies from ship to shore, but in the revised concept of operations, the two ULS were instead re-allocated to the seabase as a "connector" to ground troops. The players also allocated an additional large ULS to the LCE (MCWL: FR 2017). Table 2 depicts the scenario's initial and revised ULS locations.

Table 2. Initial and Revised Locations of the Small, Medium, and Large ULSs. Adapted from MCWL (2017).

	Initial			Revised		
Units | ULS	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
Seabase	-	-	-	-	-	2
ACE	-	-	2	-	-	-
LCE	1	6	-	1	6	1
BN	5	-	-	4	6	-

5. Wargame Conduct

Upon development of the overall MCWL wargame scenario, it was broken down into three smaller vignettes. Cells made up of approximately 25 players studied each vignette and planned, discussed, and refined their concept of ULS sustainment. The cells conducted this assessment while using the consumption and supply modeling data provided by Operations Analysis Directorate (OAD) (MCWL 2017). The initial concept of operations for the ULSs focused on a hub-and-spoke method of logistics distribution, with the seabase and the LSA being the hub of logistic throughput (MCWL 2017). Other units (i.e., companies) could further distribute supplies via their own organic ULSs to their dispatched small units. This initial concept of operation can be seen in Figure 7. Also of note, the wargame players assumed that each ULS used a "point-to-point-delivery" for logistics re-supply, meaning that the ULS would deliver supplies directly to the requesting unit from the supplier (MCWL 2017). The players synthesized these outputs into recommendations for future ULS concepts of operations and employment.



In this scenario, large ULSs ferry supplies from the seabase to the LSA (LCE) or the BN, and medium and small ULSs deliver supplies to small units.

Figure 7. Initial MCWL Wargame Concept of Operations. Source: MCWL (2017).

6. Conclusions

The MCWL wargame drew conclusions about concepts of operations for ULSs and produced input for future ULS work. The wargame insights discussed issues ranging from containerization of supplies to the size of each specific ULS. This section details only those conclusions that are pertinent to the thesis.

One of the major changes resulting from the wargame was the allocation of ULSs as detailed in Table 2. This change in allocation corresponds to a change in operating concept. The final concept put more emphasis on throughput via large ULSs from the seabase to requesting units.

According to the wargaming results, each size of ULS is best suited for just-in-time-delivery to isolated elements, and other logistics platforms most efficiently moved the bulk of logistic requirements due to the limited ULS capacity (MCWL 2017). ULSs should ease the ACE's sustainment burden so that ACE platforms can instead be used for combat missions. They also specified that "turn-around" (i.e., load/unload, maintenance, or other time spend for ULS redeployment) time for the large ULS was more important than airspeed (MCWL 2017). Payload capacity was also found to be important.

Other recommendations were that the medium variety of ULS should have a minimum capacity of 1000 pounds, and the small ULS should have a capacity of 150 pounds. The small variety should also be man-portable and survivable. Also of note, the players recommended robust C2 systems for the supported and supporting units so that all aspect of the logistics process could be viewed and monitored by all users at all times across a dispersed battlefield. The MCWL scenario and results informed research conducted by OAD, and both MCWL's scenario and OAD's analysis influenced the development of this thesis.

B. OAD STUDY

Based on the results of the MCWL wargame, OAD conducted its own analysis relating to ULS concept of operations, speed, and payload capacity. Most importantly to this thesis research, however, were its analyzed concepts of operations and assumptions for analysis. OAD's research consisted of five concepts of operation. These concepts are detailed in Table 3.

Table 3. The Differing Concepts of Operation for Logistics Throughput from OAD's Analysis. Adapted from Capabilities Analysis Branch [CAB] (2017)..

CONOPS	
1|Baseline	LSA → BLT → COs → PLTs
2|BLT Hub & Spoke	LSA → BLT → All other nodes
3|LSA Hub & Spoke	LSA directly to all other nodes
4|Seabase Hub& Spoke	Seabase directly to all other nodes
5|Alternate Baseline	LSA → BLT and I CO (I CO to L CO), COs → PLTs

The CONOPS analysis either began at the LSA or the Seabase.

As seen in Table 3, in the baseline scenario, supply flows from the unit with the supplies (i.e., a larger unit, farther away from direct combat action) to the unit that needs the supplies (i.e., a smaller unit on the ground that is farther from the sea). This type of resupply follows a linear or hierarchical method and is a typical chain of resupply. Besides the alternate baseline, the rest of the concepts are termed "hub-and-spoke." These concepts only differ from each other based on which unit is the hub. Supplies flow into the designated hub, and flow out to all remaining units.

In addition to the concept of operations analyzed, the assumptions used for the study are also important for this thesis research. OAD first calculated the DOS and DOA for each unit in the scenario and then assumed that the ULSs could not transport all of the daily supplies. They therefore based their calculations on the transport of one-third of each unit's daily supplies. The assumptions also included that medium ULS should be loaded to at least 60% capacity before departing, that the total ULS trip time was calculated by adding flight time and 30 minutes of load and unload time, and that ULSs could only operate for 16 hours a day due to crew day requirements (CAB 2017). Finally, they assumed that with the exception of CONOPS 4, the scenario starts with supplies already at the LSA (CAB 2017). Both the concept of operation and assumptions used by OAD in its analysis influenced this thesis scenario.

C. THESIS SCENARIO

This research scenario explores logistic sustainment ashore after an amphibious landing has occurred, and individual units have established themselves in the conduct of dispersed combat operations. The mission, concept of operations, units, and ULS types bear many similarities to the MCWL wargame.

1. Mission

The overall scenario mission remains the same: conduct operations to defeat enemy aggression in support of a local friendly government and its territories. However, the mission pertaining to this scenario focuses specifically on the logistics aspect of support (the part of the mission conducted by the LCE). The LCE mission is to logistically resupply dispersed units via ULS in order to support combat operations.

2. Units

The units used for this scenario are similar to the MCWL wargame. The seabase, or SEA, is the start of the chain of logistics. The LCE and the GCE are the main logistics and ground force units, respectively. CO1 and CO2 are the two companies and each company has two platoons (PTL11 and PLT12 belong to CO1, while PLT21 and PLT22 belong to CO2).

Each unit is a node within the logistics sustainment system. Supplies and requests for supplies flow through the system nodes, or units.

3. ULSs

Small, medium, and large ULS are used for the scenario, but their specific capabilities are not constant throughout. ULS capabilities, like speed and payload capacity, become variable inputs when running the simulation. Specific ranges of inputs will be discussed more thoroughly in later thesis chapters. Enemy units also continue to create risk for the ULSs.

4. Logistics Process and Concept of Operation

The logistics process is the focus of this model and details the flow of supplies throughout its life cycle. Each unit, based on its number of personnel, consumes supplies at a given rate. The using unit, or unit that is consuming supplies, requests supplies from another unit, once they deem it necessary. This request for resupply can be triggered by a pre-existing resupply level or in preparation for a future supply need. The unit receiving the request must check its inventory on hand, and if it has enough supplies available, it schedules transportation to take the supplies to the requesting unit. Once moved, transportation returns to its owning unit. This process repeats itself until supplies are exhausted or the mission, and thus the need for supplies, has ended. The concept of operations that control how supplies are moved through the logistic process are the linear and hub-and-spoke methods.

a. Linear Method

For purposes of this thesis, the typical method of Marine Corps logistic movement is termed the linear method, and mimics OAD's base line concept. This method is a hierarchical method in which a smaller unit (i.e., a platoon sized unit) requests and receives supplies from their higher unit (i.e., a company sized unit). Requests for supply and supply fulfillment are performed only with units that are directly higher or lower in a unit's chain of organization. In this way, supply originates from the SEA, travels to the LCE, to the GCE, and is then dispersed to the companies. The companies in turn distribute to their respective platoons. ULSs are allocated to each unit, and logistics throughput is dependent on the quantity of supplies the ULSs can ferry. The sizes and numbers of systems become inputs to the simulation. These varying levels are described later in Chapter 3, Section D. This linear method of logistics simplifies the tracking and movement of supplies, ultimately ensuring that units are being resupplied. A pictorial description of this linear logistics process can be seen in Figure 8.

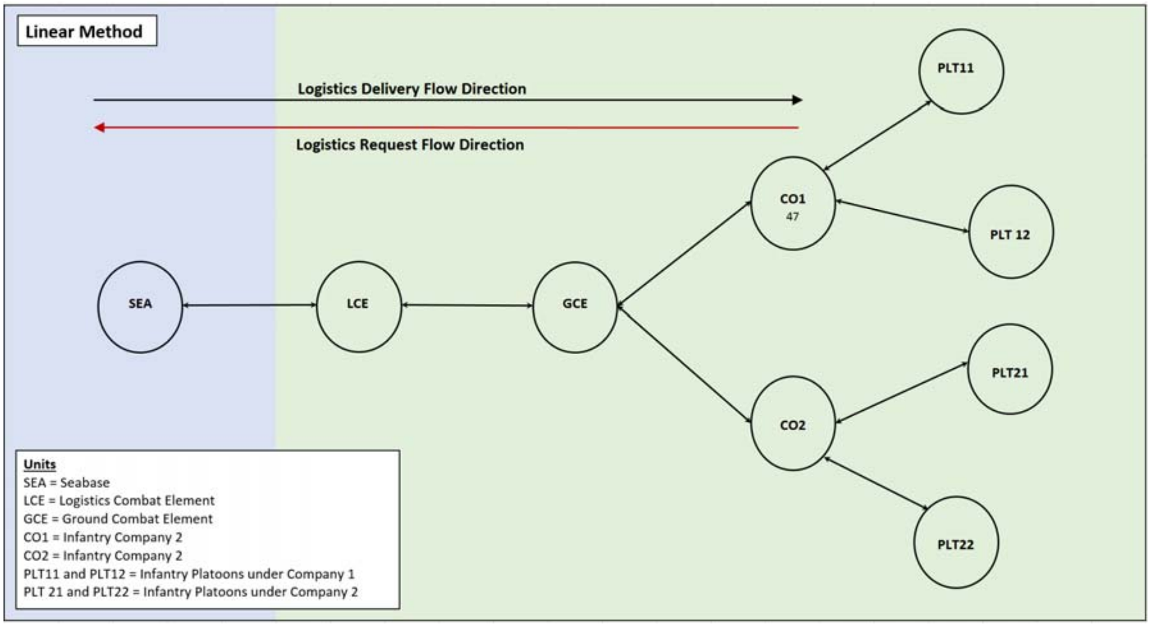


Figure 8. Flow of Supplies and Requests for a Linear Logistics Resupply Method.

b. Hub-and-Spoke Method

The hub-and-spoke method of resupply is based on one unit logistically supporting other combat units, and is similar to OAD's third concept. Allowing one unit (i.e., the LCE), to support the majority of the units in the GCE streamlines logistics processes and allows the GCE to focus on combat. The LCE in effect becomes the hub and the units in the GCE become the spokes. While this method streamlines the logistics process, it also requires more effort to track and control supply levels. Because supply is not moving linearly through the hierarchical chain, it is harder for units to track what their subordinates have or need.

ULSs are again allocated to each unit and throughput is dependent on the capabilities of the ULSs. The sizes and numbers of ULSs continue to be inputs to the simulation and are discussed later. Figure 9 illustrates the hub-and-spoke method.

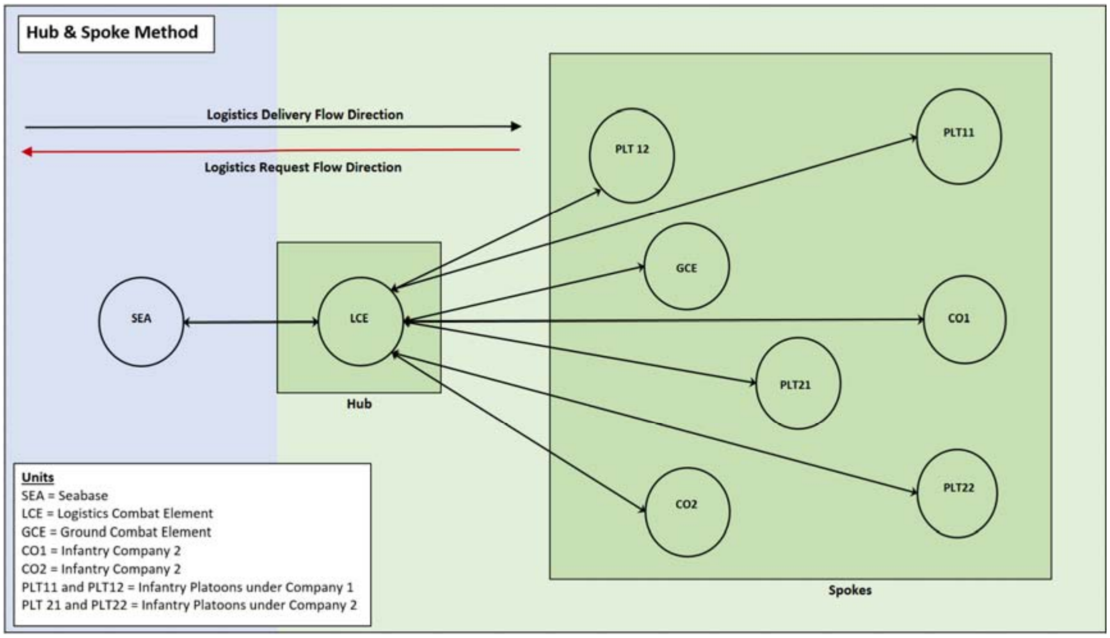


Figure 9. Flow of Supplies and Requests for a Linear Logistics Resupply Method.

The hub-and-spoke method and the linear method can also be used in concert. Depending on the situation and the unit relationships, the LCE may only act as the support hub for the GCE headquarters and the companies, and the headquarters and companies would then be responsible for resupplying their subordinate units. A mix of linear and hub-and-spoke, therefore, is also a realistic concept of logistics resupply.

5. Assumptions

To create the scenario and subsequent model, some aspects of the design are assumed due to a lack of real world data. Assumptions include:

1. The scenario begins with all units in their dispersed locations with a specified number of DOS. The assumption is that the amphibious landing has already occurred and sustainment operations are underway. Although the units are in place at the beginning of the simulation, there will be some subsequent movement during the conduct of the operation due to patrol movement. This variability in distances is taken into account within the model.

2. In regards to supply availability, the assumption is that the seabase is stocked with enough supplies for the entire operation, and thus never runs out. To assess how ULS sustainment responds to demand, there must be a

constant logistics supply from somewhere, and in this case it is from the seabase.

3. The ULSs move from point to point. They originate at the supplying unit (the unit to which the ULS is allocated) and they deliver supplies to a single requesting unit before returning to their owning unit.

4. The medium and large ULSs have to be at least partially full in order to deliver supplies. This percentage is a factor in the simulation.

5. ULS mechanics is not a topic of this thesis, so the technicalities of flying and containerization of supplies are not examined. If the weight of the requested supplies is under the ULS's payload weight, then the ULS can deliver the supplies.

6. The system assumes a communication system that enables units to request supplies with minimal delay. This assumption is unrealistic in the real world due to the prevalence of degraded communication networks and personnel inefficiencies, but is used for this model to test supply chain inefficiencies.

7. To account for the total time it would take between request and delivery, future developmental and operational testing should quantify loading, unloading, and maintenance times. In this model, it is assumed that load, unload, and maintenance time length increase proportionally with the size of the ULS. The larger the ULS, the longer it takes to load/unload and maintain. Maintenance is performed every round trip, and attempts to quantify the basic maintenance checks and troubleshooting needed for continuous operations. It is not meant to include extensive levels of maintenance. The nominal maintenance time for each ULS size is treated as a variable input to the model.

8. There is no queue for loading/unloading or for maintenance. This assumes that there are enough logistics personnel available to perform ULS related missions. As the ULSs are handling some of the burden usually reserved for alternate re-supply methods, those personnel normally engaged would be free to support ULS operations.

9. Because the ULSs operate in a low to medium threat environment, their operation carries risk from enemy combatants. Weather and maintenance failures also create risk to the systems. These risks are rolled up into a single risk percentage that attempts to quantify total risk to ULSs. This risk is treated as a nominal input to the model. If an extensive maintenance failure occurs, the ULS is considered "lost" and thus unavailable for future operations.

10. The number of Marines remains constant throughout the course of the simulation. While ULSs can be lost, Marines cannot. This also means that

unit requirements remain the same throughout the course of the simulation run.

11. Operational risk in the model is assumed to be a worst case scenario. If a ULS is lost, it cannot enter back into operations and its payload is also lost.

12. In the linear method of re-supply, each unit's inventory on hand (IOH) and re-order point (ROP) are calculated based on that unit's personnel numbers and all of their subordinate unit's personnel numbers. (I.e., a platoon would only calculate based on their personnel numbers but a company would calculate based on their and their subordinate platoon's personnel numbers). This ensures that the units are requesting enough supplies when they go under their ROP. With the hub-and-spoke method, however, the LCE is the only unit that re-orders supplies based on other units' personnel numbers.

These assumptions provide clarity to the scenario and explain in part how the model is built.

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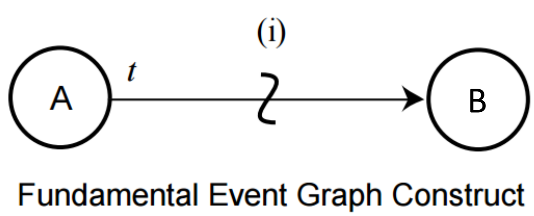
III. MODEL

Chapter III focuses on the discrete event simulation (DES) created to model the scenario from Chapter II. Using DES to model the logistics process has been previously accomplished, namely, in modeling the operational pace of a Marine Expeditionary Brigade's GCE as compared to the LCE's ability to support (Miner 2006). This model uses SimpleKit-python (Oliver and Sanchez 2015), a free software package that performs DES in the Python programming language. The model code is available upon request to the author. Generally, a system is a "collection of entities…that act and interact together toward the accomplishment of some logical end," and models are used to gain insight into such a system and how it functions (Law 2007). In this research, the system being studied is the logistics chain from the seabase to small units conducting dispersed operations.

A. DISCRETE EVENT GRAPH MODELING

This logistics process and model is classified as a discrete system. A discrete system is one in which variables representing different parts of the system change at different points in time (Law 2007). An event graph pictorially depicts a DES. An example of an event graph can be seen in Figure 10. Event graphs consist of state variables, events, parameters, and "scheduling relationships" as they relate to simulation's events (Buss 2004).



If (i) is true, event A schedules event B to occur after time *t*. Time *t* can be instantaneous or can be a designated amount of time.

Figure 10. Basic Event Graph Construct. Adapted from Buss (2001).

The model is also stochastic, and so even with the same inputs, the model will produce different outputs. This randomness is built into the model through distributions that will be detailed in Section C, and is similar to what could happen in a real world scenario; even if all of the mission characteristics are very similar, the outcome will never be exactly the same.

1. States

The results of these actions at any point in time while running the model describe the system's "state." A state is "that collection of variables necessary to describe a system at a particular time, relative to the objectives of a study" (Law 2007). State variables can and do change over the course of a simulation, and this change occurs when a related event occurs (Buss 2004).

2. Events

Events are transitions between states that occur at specific points in time (Buss 2002). These events are managed on the Event List, a type of "to-do" list for the simulation, keeping track of the scheduled event and the time it should occur (Buss 2001).

3. Parameters

Parameters are elements that do not change over the course of the simulation run (Buss 2004). An example of a parameter for this simulation is the payload of the ULS.

4. Scheduling Edges

Scheduling edges can perform the following routines: "transform state variables," "generate edge delay times," "test event incidence conditions," or "schedule or cancel further events" (Schruben 1983). Usually these scheduling relationships are based on conditional logic, such as if-then statements. For example, if something occurs at event A, then event B would be scheduled. This logic can be used to schedule multiple events that are a result of a single event.

5. Time Delays

A time delay is the delay in a state transition. The delay occurs when an event is scheduled, and can cause the transition to happen instantaneously or after a prescribed amount of time.

B. MODEL CLASSES

The model code is based around several classes. Classes can be created as part of the Python programming language, and these classes have Object Oriented Programming features. Once an object has been created, data can be assigned to the object (Python Software Foundation [PSF] 2017). This thesis model has four classes. The classes are:

- **ULS** object that defines ULS system characteristics,
- **Unit** object that defines the unit and stores the unit's supply levels,
- **Totals** object that records running totals for the classes of ULS per unit, and
- **SimpleKit** object that runs the model. The SimpleKit object contains the main code for the model, including all of the rules for supply movement throughout the logistics process, and uses the ULS and unit objects to track and update supply levels.

1. ULS Object

The ULS object contains data on the ULSs. Model system inputs generate these parameters, which remain constant within a simulation run, and generates outputs that vary based on simulation run. For each input, ULS object data includes:

- **ID**: identification based on whether it is a small, medium, or large ULS.
- **Size:** size of the ULS (small, medium, large).
- **Speed**: maximum speed capability in km/hr.
- **Payload**: maximum payload in pounds.
- **Maintenance Time**: average time in minutes that the ULS needs maintenance after every round trip.
- **Load Time**: average time in minutes it takes to load the ULS.

2. Unit Object

The Unit object contains data on the units. Model system inputs generate this data, which vary based on simulation run. For each input, unit object data includes:

- **ID:** individual identification, based on the size and subordination of the unit. The units IDs that are just based on size are SEA, LCE, and GCE. CO1 and CO2 differ by one number, but the PLTs have two numbers (ex. PLT11). The first number is the company the platoon falls under and the second is the platoon’s number.
- **Size:** size of the unit.
- **Designation 1:** used for platoons and companies to delineate company affiliation. For all other units, this becomes a zero.
- **Designation 2:** used for platoons to delineate platoon number. For all other units, this becomes a zero.
- **Number of Personnel**: number of personnel in the unit.
- **Initial DOS**: the initial days of supply each unit has on hand at the start of the simulation.
- **Inventory On Hand (IOH):** running total of the pounds of supplies that each unit has at any point in time.
- **Re-Order Point (ROP):** supply level that necessitates the ordering of more supplies.
- **Small ULS:** the number of small sized ULSs a unit possesses.
- **Medium ULS:** the number of medium sized ULSs a unit possesses.
- **Large ULS**: the number of large sized ULSs a unit possesses.
- **Supply Status:** seven rolling data points that record the state of the logistics system at any point in time. The statuses will be explained more fully later, but unit supply inventories can be:

  1. Short
  2. Required but not requested
  3. Required and requested
  4. Waiting for the request to be filled
  5. Pending an available ULS

6. En-route

7. Filled

3. Totals Object

The Totals object contains data relating to each unit's classes of ULSs. These state variables are updated within the SimpleKit object as the simulation progresses. For each data point, totals are kept for each ULS class (i.e., small, medium, large) in each unit. These totals include:

- **Supplies Received:** running total of amount of supplies, in pounds, each unit receives.
- **Trips:** number of round trips each ULS class by unit completes.
- **Supplies Transported:** amount of supplies, in pounds, each ULS class by unit can transport.
- **ULSs Lost:** number of ULS lost during the course of the simulation.
- **Distance ULS Travelled:** total distance in kilometers travelled by ULS class by unit.
- **Load Time:** total time it takes to load and unload, in minutes, each ULS class by unit.
- **Maintenance Time:** total time it takes to perform maintenance, in minutes, on each ULS class by unit.
- **Flight Time:** total flight time, in minutes, for each ULS class.

The data associated with the Totals object will be used for analysis after the design of experiments.

4. SimpleKit Object

Unlike the ULS and unit objects that just hold data, the SimpleKit object also contains rules for scheduling events. These rules are the basis for the orderly conduct of the logistics system. The SimpleKit events and rules are discussed in the following paragraphs.

C. MODEL EVENTS

1. Introduction to Events

The main DES, and specifically the SimpleKit object, is broken up into six basic events. These events correspond to where supplies are within the logistics system at any point in time, and contain the rules for scheduling other events.

2. Initialize

The first event of the DES is initialization. This only occurs once, and organizes model data based on initialization rules. It reads the inputs to the model and assigns the data to the correct storage areas for use throughout the rest of the model. The initialization event uses the input data to create the correct number of ULS and unit objects. The initialization phase also specifies the length of the simulation run and schedules the next event, which is the consumption of logistics.

3. Consume Logistics

Once the DES initializes and schedules the consumption of logistics, specified DOS are subtracted from each unit's IOH based on a specified time period. After the initial consumption, consumption is re-scheduled for as frequently or infrequently as needed. In this event, every unit's reorder point (ROP) is also checked against their IOH. If the IOH is less than the ROP, then a request for supplies is scheduled.

4. Request Logistics

During this event, supplies are requested for all units that are short supplies. Once the request is made, an inventory check is scheduled.

5. Check Inventory

During this event, inventory levels are checked to see whether subordinate units can be resupplied. This check is dependent on whether the resupply method is linear or hub-and-spoke. If resupplying via the linear method, then the resupply request goes to the next higher unit, and if that unit has enough supply, a fill request is scheduled. To have enough inventory to resupply, a unit's IOH must be greater than one DOS for that unit plus the subordinate unit's requested supply amount. If the higher unit does not have enough supplies, then the unit becomes short of supplies and a request for logistics is scheduled. Once the higher unit has enough supplies, then the subordinate unit's fill request is scheduled.

For the hub-and-spoke method, all logistics requests go to the LCE instead of the requesting unit's next higher unit and the LCE checks its inventory. To have enough inventory to resupply, the LCE's IOH must be greater than one DOS for the LCE plus the subordinate unit's requested supply amount. If the LCE has enough inventory, then a fill request is scheduled. If the LCE does not have enough supplies, then it schedules a request for logistics with the SEA. The SEA, for purposes of the model and because of its placement as the most "senior" unit in the chain of logistics, never runs out of supplies.

6. Fill Request

Once a unit has requested supplies, and its higher unit has checked that they have enough supplies in inventory, a fill request is scheduled. During this event, the supplying unit checks its on-hand ULS inventory. If the unit has an available ULS, then a delivery is scheduled. If there is not a ULS available, then the delivery is paused until a ULS returns to the inventory and the delivery can be scheduled. The specific rules for filling a request are as follows:

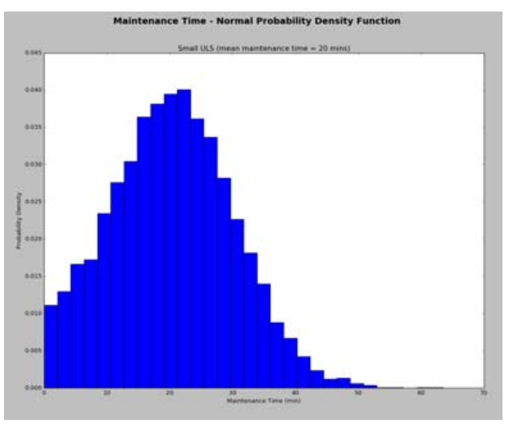
- Medium and large ULSs must be filled to a specified capacity before departure. This capacity requirement is a specified input to the system ranging from 30% to 80% of the ULS's payload.
- Small ULSs do not have a minimum capacity fill requirement.
- ULSs are checked and assigned based on size. Large ULSs are checked first, and if supply capacity thresholds are met (i.e., supplies exceed the large ULS's payload or supplies exceed the capacity requirement), then the delivery is scheduled for transport by the large ULS. Once the determination is made for the large ULS, if more supplies are to be delivered, then the medium and, lastly, the small ULS deliveries are scheduled.

7. Deliver Logistics

After checking for an available ULS, the logistics delivery is scheduled. When this event is scheduled, the preceding event also passes information relating to the requesting and supplying unit the amount of supplies to be transported, and the type of ULS that has been assigned the job of transporting. This information is used to calculate the time it takes for the delivery.

This event uses random variables based on nominal maintenance and load times, ULS speed, and distances between units, to create variability within the model. This attempts to simulate the unpredictability inherent to real world operations. Of note, because there cannot be negative times, distances, or speeds, the model truncates the distribution at zero by taking the absolute value of the noted distribution. These nominal inputs are based on distributions and include:

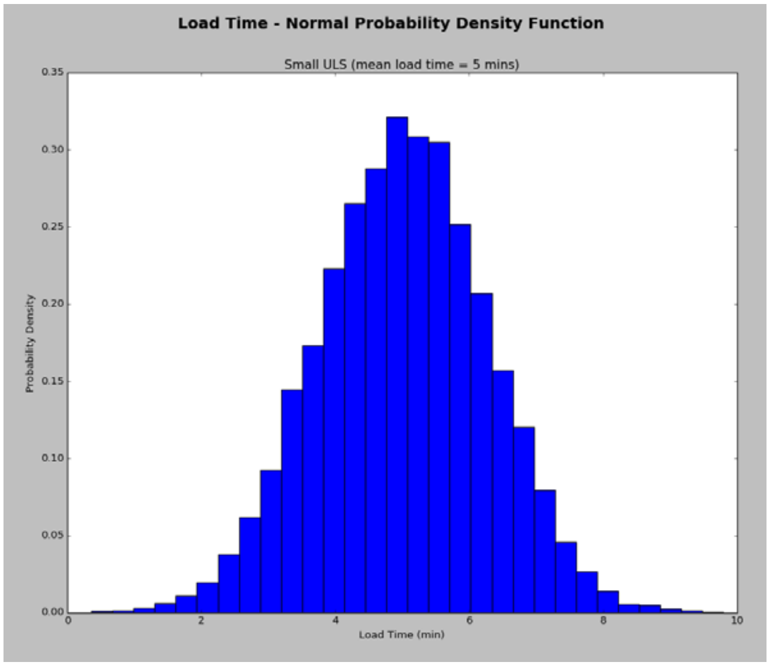
- **Maintenance Time:** generated from a normal distribution. This distribution uses the nominal maintenance time for the specified ULS size and a standard deviation of 50% of the nominal time. Maintenance time is more variable than load time because of the breadth of what could go wrong, the variable skill of maintainers and their ability to troubleshoot equipment, and the time it can take to receive needed parts. Maintenance is inherently unpredictable. Figure 11 depicts an example probability density function for a truncated normally distributed maintenance time.



This normal distribution illustrates the range of values that the model could generate per factor; in this case, a small ULS's average maintenance time of 20 minutes.

Figure 11. Example of Data Generated from the Probability Function for Maintenance Time.

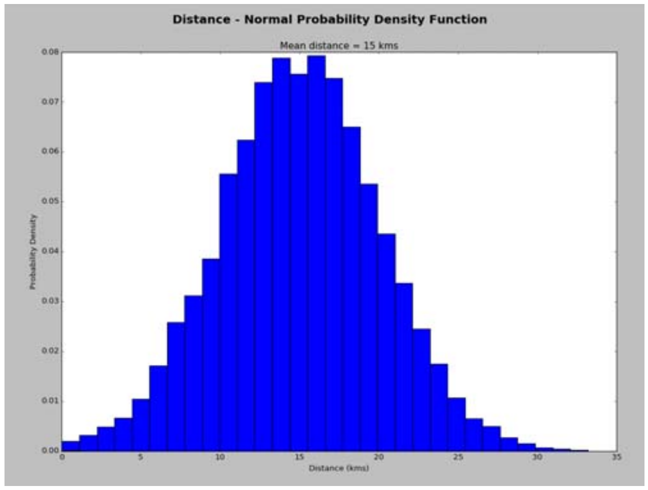
- **Load Time:** generated from a truncated normal distribution. Values below zero would be truncated, but these are rare. This distribution uses the nominal load time for the specified ULS size and a standard deviation of 25% of the nominal time. The standard deviation for the load time is less than that for the maintenance time because loading is usually a streamlined process and thus less variable. Figure 12 depicts an example probability density function for a normally distributed load time.



This normal distribution illustrates the range of values that the model could generate per factor; in this case, a small ULS's average load time of 5 minutes.

Figure 12. Example of Data Generated from the Probability Function for Load Time.

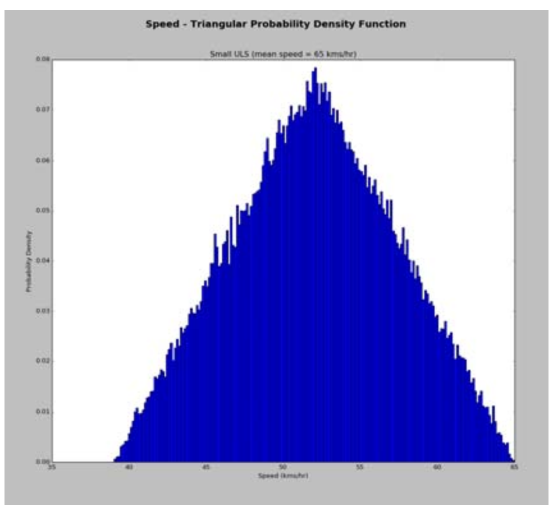
- **Distance:** generated from a truncated normal distribution. This distribution uses the nominal distance between two units and a standard deviation of 33% of that nominal distance. Any negative values are truncated by taking the absolute value. Figure 13 depicts an example probability density function for a normally distributed distance.



This normal distribution illustrates the range of values that the model could generate per factor; in this case, a distance of 15 kms.

Figure 13. Example of Data Generated from the Probability Function for Distance.

- **Speed:** calculated from a triangular distribution. The lower limit of the ULS speed is 60% of the input speed for the specific ULS size, the mode is 80%, and the upper limit is the max speed. The MCWL wargame specified that ULSs would operate at 80% of their max operating speed, and so most transit speeds will occur closer to the 80% mark with slight variation on either side. Figure 14 depicts an example probability density function for a triangularly distributed speed.



This triangular distribution illustrates the range of values that the model could generate per factor; in this case, a small ULS's speed of 65 kms/hr.

Figure 14. Example of Data Generated from the Probability Function for Speed.

Once the total trip time to deliver the supplies is calculated using the random variables, the ULS's return trip is scheduled.

8. Return Transportation

The last event in the DES, the transportation return event, determines if the supplies are successfully delivered to the unit, updates the unit's supply levels and ULS availability numbers, and, if it is successful, calculates the return flight time. To determine if the ULS is lost, the event has an input for risk to the system. This input could be a quantifier for risk to ULSs from mechanical failure, weather, or enemy combatants, but for purposes of this thesis functions to add realistic variability inherent in real world operations. In this case, if the risk exceeds the threshold for the ULS delivery run, the ULS and the supply payload it carries are lost and are no longer seen within the scope of the simulation. This models the worst case scenario because the ULS and load are both lost. The supplies must be re-ordered and the supply fulfillment must occur with one fewer ULS. The event then updates the receiving unit's supply levels and ULS availability, and calculates the return trip time based on unload and flight time.

9. Event Conclusion

The events within the SimpleKit class are the driving force behind this DES simulation and ensure that the model functions in a way that mimics real world logistics resupply. Because of the variability within the system, the number of units and ULS, and the simultaneous demands on the system, the events ensure the correct scheduling between events. The complete event graph can be seen in Figure 15.

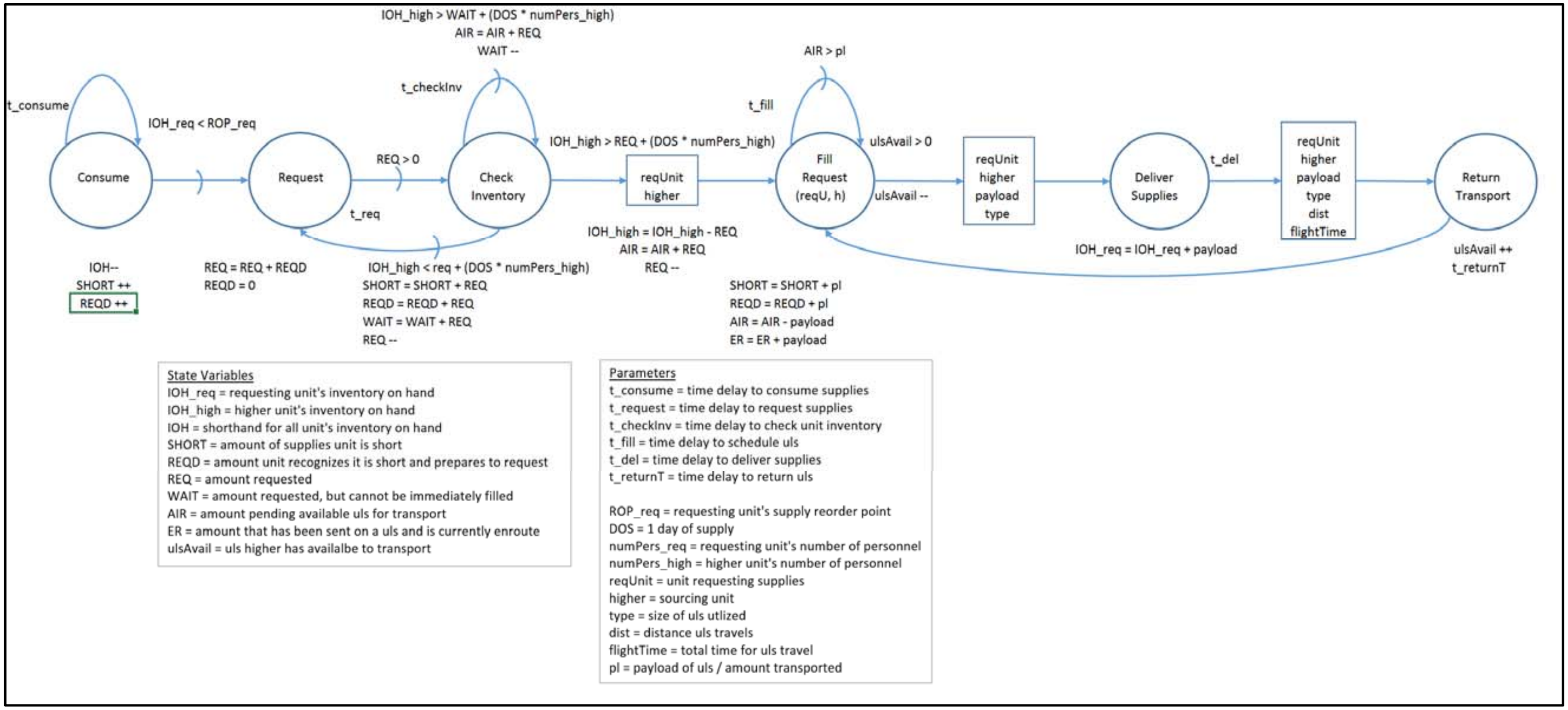


Figure 15. Model Event Graph.

D. MODEL INPUTS

The model inputs are a starting point for running the simulation. While fixed parameters have already been discussed for use in the model, there are other model inputs, called factors, which can be varied by manipulating the input file. These factors allow for the exploration of alternatives using a designed experiment that runs the simulation for carefully-chosen combinations of these factors. These experiments are explained in Section E and Chapter IV. For ease of organization, these factors are broken down into five categories: ULS capabilities, the distribution of ULSs to specific units, unit data, distances between units, and other inputs. These variables include the ranges over which each variable will be simulated, and these ranges become factors in the design of experiments.

1. ULS Capabilities

ULS capability factors depend on the size of the ULS. These factors are run as inputs to the simulation, and ULS flight times are calculated based on this data. Factor ranges are detailed in Table 4 based on the MCWL wargame and subsequent OAD analysis.

Table 4. Baseline Inputs for the ULSs.

ULS Capability Factors			
Small ULS	*Min*	*Max*	*Levels*
Payload Weight (lbs)	50	150	101
Speed (km/hr)	55	75	21
Load Time (min)	1	10	10
Maintenance Time (min)	1	60	60
Medium ULS	*Min*	*Max*	*Levels*
Payload Weight (lbs)	600	800	201
Speed (km/hr)	50	140	91
Load Time (min)	1	25	25
Maintenance Time (min)	1	120	120
Large ULS	*Min*	*Max*	*Levels*
Payload Weight (lbs)	3500	5000	512
Speed (km/hr)	100	500	401
Load Time (min)	1	75	75
Maintenance Time (min)	1	180	180

Each factor has a range of integer-valued inputs for use during the design of experiments and this corresponds to the maximum number of integer-valued levels in a full factorial design.

2. ULS Distribution

ULSs are assigned to specific units for resupplying their subordinate units. Based on the MCWL wargame, different numbers and sizes of ULSs are assigned to units. These variable factors can be seen in Table 5.

Table 5. Available ULSs per Unit.

Available ULSs per Unit			
	Ranges of ULS Numbers		
Unit	Small ULS	Med. ULS	Large ULS
SEA	-	-	1 - 5
LCE	1 - 15	1 - 15	0 - 3
GCE	1 - 15	1 - 10	-
CO2	1 - 15	-	-
CO1	1 - 15	-	-

Each unit is assigned specified numbers of ULSs and these become factors for the design of experiment.

3. Unit Inputs

Units in the model have specific data that act as factors. The data ensures that the simulation is able to run, is augmented from the MCWL wargame, and can be seen in Table 6.

Table 6. Unit Inputs. Each Unit has Specific Descriptive Data.

Unit Inputs									
	Units								
Inputs	**PLT11**	**PLT12**	**PLT21**	**PLT22**	**CO1**	**CO2**	**GCE**	**LCE**	**SEA**
Number of Personnel	43	40	37	29	29	33	35	35	0
Initial Days of Supply (DOS)	2 - 4	2 - 4	2 - 4	2 - 4	2 - 4	2 - 4	2 - 5	2 - 5	15
Re-Order Point (ROP)	Same as unit’s Initial DOS								2

4. Unit Distances

To calculate ULS flight time, the distance between units needs to be delineated and inputted into the model. Nominal distances between all units can be seen in Table 7. In order to create randomness within the simulation, the distances in Table 7 are the nominal distances used to generate ULS transit distances within the model.

Table 7. Unit Distance Matrix.

Unit Distance Matrix (km)					
	PLT	**CO1 & CO2**	**GCE**	**LCE**	**SEA**
PLT	0	15	35	125	310
CO1 & CO2	15	0	20	110	295
GCE	35	20	0	90	275
LCE	125	110	90	0	185
SEA	310	295	275	185	0

Normal distributions based on these nominal kilometer distances plus/minus 20% are used to calculate variable ULS transit times within the simulation.

5. Other Inputs

The simulation also requires additional inputs to run. These factors include:

- **Risk to ULS:** amount of risk inputted into the scenario. This can include risk due to maintenance failures, weather, and enemy disruption, and adds unpredictability to an otherwise deterministic system.
- **DOS Weight:** the simulation calculates supply levels by weight. The DOS weight is the weight of a Marine’s daily supply. For example, if just calculating DOS of MREs, 4.5 lbs (3 MREs at 1.5 lbs each) would be used as the DOS weight factor. 55 lbs is used as the input for the main scenario.
- **Logistics Distribution Method:** this input is either the linear method of resupply or the hub-and-spoke method of resupply.
- **Crew Day:** this determines how long a ULS can operate in hours. For example, the ULSs could operate continuously on a 24 hour schedule or

could operate for a more normal 16 hour day. This input also determines consumption rate.

- **ULS Fill Percentage:** this input is the percentage of the ULS payload that has to be filled before the ULS can depart and deliver supplies. For purposes of the scenario, the fill percentage ranges from 30% to 80% of the ULS payload.

- **Scenario Time:** this input is the total run time of the simulation. This translates to varying numbers of days depending on the crew day. (The main scenario takes place over 5760 minutes, which is a 6 day period if the crew day is 16 hours, and a 4 day period for a 24 hour crew day.)

E. DESIGN OF EXPERIMENTS

When the model is complete, it should be used effectively and fully. Running a large simulation with all the input combinations possible, however, requires a large amount of time and computing power. Due to the number of inputs, it is necessary to construct an efficient design of experiments (DOE) to fully exploit the simulation and gain robust results (Sanchez et al. 2015).

1. Definitions

Specific definitions must be included to fully explain DOEs. These definitions are as follows:

- **Factors:** input variables to the simulation. They can be quantitative or qualitative, discrete or continuous, binary, or controllable or uncontrollable (Sanchez et al. 2015). These factors can have a "variety of values, called levels" (Sanchez et al. 2015). Useful simulation results often include which factors are of import to the simulations responses and which combination of factors are influence results (Sanchez et al. 2015).

- **Responses:** outputs to the simulation.

- **Design Point:** a row of factor levels that act as multiple inputs to the simulation (Sanchez et al. 2015).

It is important to maximize the functionality of designed experiments. If these experiments are not fully thought out, designs could potentially only test a few combinations of factor settings or only vary one factor at a time. These inefficient designs can create confounded or one-at-a-time sampling effects (Sanchez et al. 2015). Examples of these effects can be seen in Figure 16.

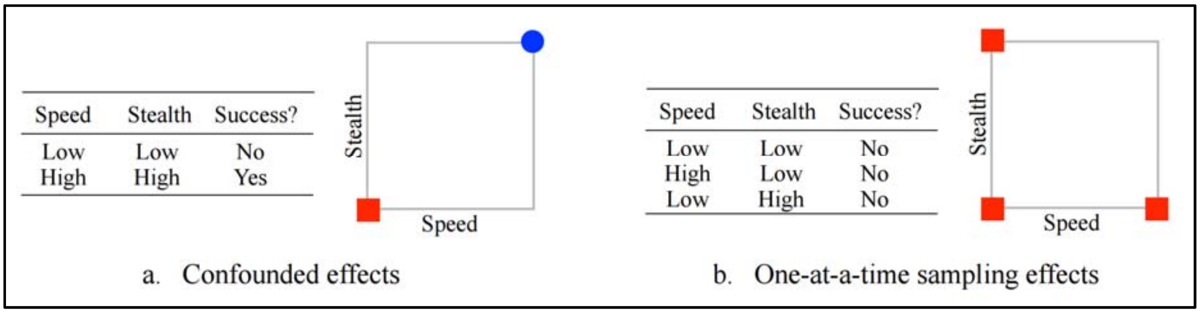


Figure 16. Unsuitable Designs do not Provide Insight into Whether Speed or Stealth is More Important. Source: Sanchez et al. 2015.

The effects in Figure 16 illustrate that efficient designs are needed to gain insightful responses to form a model. Confounding effects do not allow for the differentiation of factors, and the analyst is unable to tell which factors are important. One-at-a-time sampling is random and by only changing one factor at a time, the analyst will not be able to tell if the interaction between factors is important. To fully employ a model, well designed experiments are essential. One such design is the Nearly Orthogonal and Balanced design (Vieira et al. 2013).

2. Nearly Orthogonal and Balanced designs

This thesis utilizes Nearly Orthogonal and Balanced designs, also known as NOB designs. Nearly orthogonal means that "the maximum absolute pairwise correlation between any two design columns is minimal," and "nearly balanced means that for any single factor column, the number of occurrences of each distinct factor level is nearly equal" (Vieira 2012). This makes this design very efficient and space-filling. A partial example of a NOB design can be seen in Table 8, where the *Factor Name* is the input and the *Lo* and *Hi* delineate the span of factor levels. The simulation is run with varying factors and levels for this thesis. Specific NOB designs used for this thesis are detailed in Chapter IV.

Table 8. Example NOB Design. Adapted from Vieira (2012).

Lo	55	50	0	0	120
Hi	75	150	60	10	140
	0	0	0	0	0
Factor Name	S_Speed	S_Payload	S_Maint	S_Load	M_Speed
	56	144	10	9	136
	65	86	50	2	127
	62	137	2	2	121
	64	53	57	8	134
	71	148	10	1	126
	75	80	54	10	130
	73	94	8	1	133
	64	146	17	2	126
	58	73	55	8	139
	64	72	57	9	128
	56	51	1	2	135
	66	134	11	10	135
	63	88	43	8	137
	73	83	28	9	123
	71	121	55	3	129
	70	149	30	2	125
	73	92	8	0	133

This table illustrates a NOB design. Each column is a design point with varying continuous factor levels. The range of the factor is detailed from “Lo” to “Hi.” Each row is an example of an input for a single simulation run.

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IV. DATA ANALYSIS

Chapter IV details the specific NOB design used for the DOE, the resulting output, and data analysis. The simulation is run in the programming languages Python and Ruby, and the resulting analysis is performed in JMP Pro 13.

A. MAIN SCENARIO - NOB DESIGN OVERVIEW

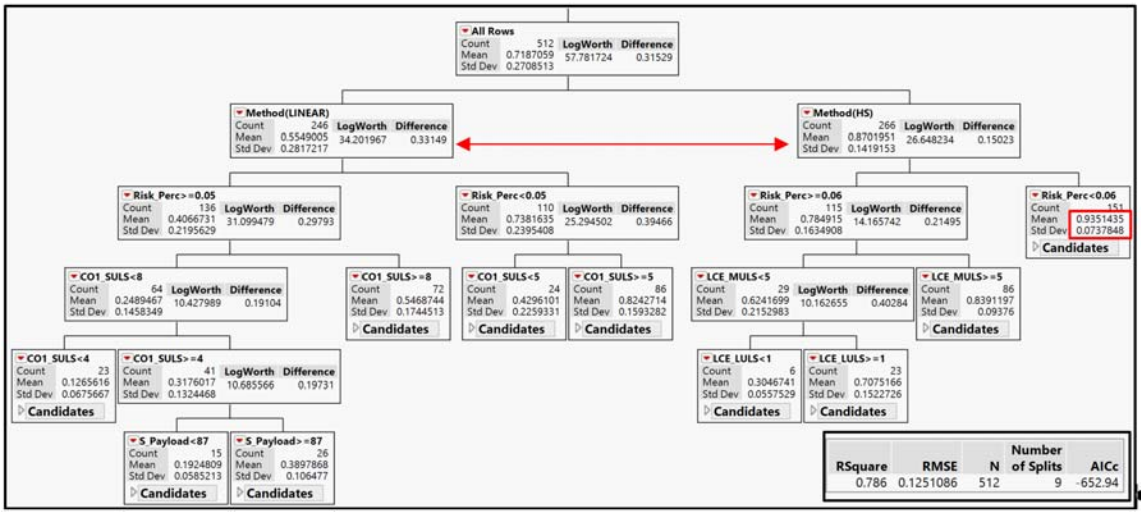
The simulation uses 164 total inputs, however, only 32 are explored as factors in these experiments. The space-filling NOB design has 512 design points, so 512 is the maximum number of levels for any of the 32 integer-valued factors. Without the NOB design, and using the same number of levels per factor, a full factorial design would have 4.07E+38 design points. The first 28 specific factors can be seen in Tables 4—6. Additional factors to this simulation include:

- **Risk to ULS:** 0 - 10%
- **Logistics Distribution Method:** Hub-and-Spoke or Linear
- **Crew Day:** 16 - 24 hours
- **ULS Fill Percentage:** 30—80%. The ULS has to be at least filled to the percentage before departing.

After designing the NOB, each design point is replicated 100 times for a total of 51,200 simulation runs. Each run produces one line of output containing the run's inputs, as well as the total number of supplies received and requested by each unit, the number of ULSs lost by each unit, and the number of trips and distance traveled by the ULSs. This output is used to measure performance. One performance measure is the average amount of successfully delivered supplies. The amount of successfully delivered supplies is calculated by considering the amount of supplies received out of the amount of supplies requested for each simulation replication. This produces the percentage of successfully delivered supplies per simulation run. The percentages are then averaged across design points. This creates 512 different scenario results based on input variations. The analysis uses partition trees, box plots, and regressions, to analyze the simulation output.

1. Partition Trees

Partition trees split factors into groups that best predict a given desired response. For the case of this scenario, partition trees examine the 32 factors to select which ones best predict the average supplies that are successfully delivered. The trees branch at different levels for each unit, offering insights for ULS employment at each unit level. Figure 17 illustrates the partition tree for PLT11.



The red line indicates the first branch of the tree and thus the most important for successful resupply. The red box illustrates the branch that results in the highest re-supply rate.

Figure 17. PLT11 Partition Tree Shows Important Factors for Successfully Delivered Supplies.

As seen in Figure 17, there are splits in the tree that illustrate what factors are important for successfully delivered supplies to PLT11. While this is the partition tree specifically for PLT11, analysis of the other platoons produced similar results. These insights include:

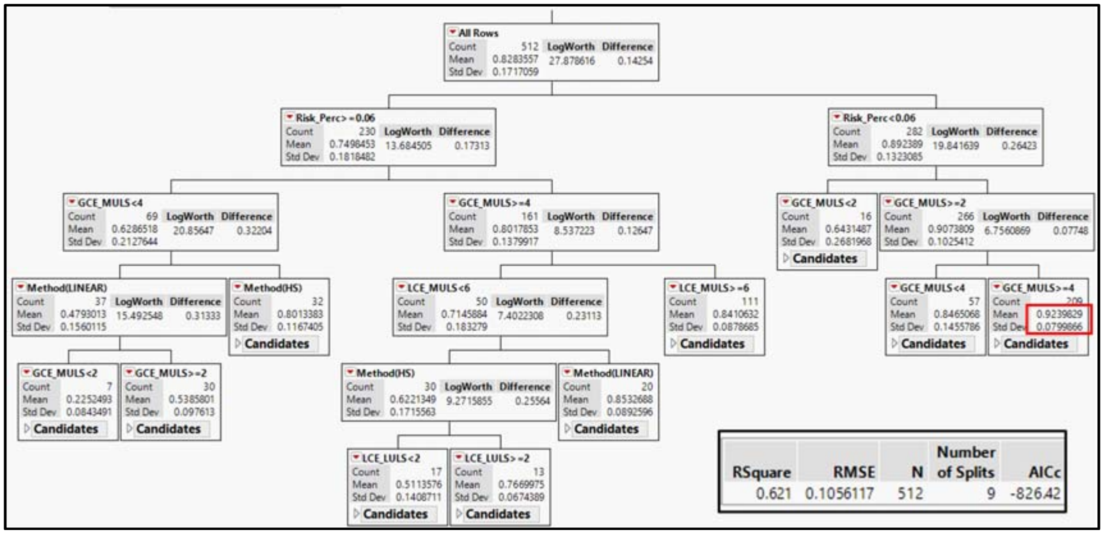
- The re-supply method is the first split in the tree and shows that the hub-and-spoke method has a large effect on supply delivery, resulting in an average of 87% of supplies delivered from requests. For the case of PLT11, re-supply method employing the ULSs is more important than any system specification.

- For both the linear and hub-and-spoke methods, risk is the second split in the tree, splitting at 5% and 6% respectively. This risk measure attempts to quantify some of the chaos that occurs in the logistics system (i.e., maintenance failures, weather, probability of enemy kills, etc.), and shows that minimizing the risk by having a survivable and reliable system is important to re-supply success. After the split between re-supply methods, the hub-and-spoke branch splits again at risk. While low risk performs well, high risk can be mitigated by adding more M-ULSs or L-ULSs at the LCE level.

- For both re-supply methods, the number of ULSs have an effect on the process. The number of S-ULS at the company level have an effect for the linear method, and the number of M-ULSs and L-ULS at the LCE have an effect for the hub-and-spoke method. This can provide an estimate of the number of ULSs needed at every unit.

- One of the splits includes the S-ULS's payload size and is the only time in the partition trees that a ULS capability appears as a branch. It splits at a payload of 87 lbs. This is an increase of 40% in payload when compared to MCWL's S-ULS payload of 50–55 lbs. This demonstrates a catch-22 with employment and capability measures: to be of use, the S-ULS has to be bigger, but if it becomes bigger, the ULS is no longer small. This indicates that S-ULSs are not useful for conducting sustained throughput operations, but that they could be useful for just-in-time logistics which typically involve small payload requirements for items that are not normally requested.

The partition tree for PLT11 provide insights into ULS employment, as well as important factors related to successful re-supply. These factors are more closely examined in this chapter's remaining sections. Partition trees also elucidate trends within other units in the scenario. Figure 18 shows CO1's partition tree.



The red box illustrates the branch that results in the highest re-supply rate.

Figure 18. CO1 Partition Tree.

Figure 18, while a partition tree for CO1, is also representative of re-supply trends found for CO2. These trends include:

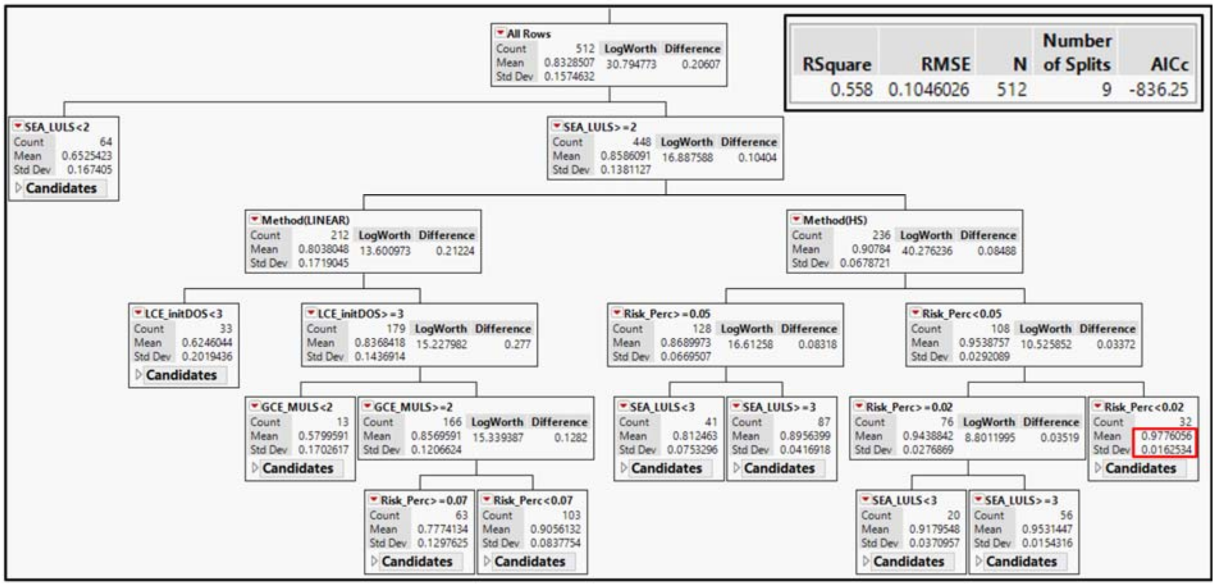
- Risk, as opposed to re-supply method, is the most important factor for predicting the average amount of supplies delivered to CO1 per requests, with the split occurring at 6% risk. Risk is also the most important factor for the GCE; however, the differentiation in risk occurs at 8%. This departure from the platoon trends (in which the re-supply method is the first split) appears to indicate that the units that are closer to the LCE, or the re-supply hub, are more affected by risk.

- Both the company and GCE trees show that the number of medium and large ULSs at the GCE and LCE level have effects on the logistic system. Rather than specific capabilities, the number of ULSs has an impact on successful re-supply.

- The re-supply method also appears to have an effect on the ratio of supplies delivered for both the companies and the GCE, but it is less important when compared to the importance of method for the platoons. The units that are farther away from the LCE (i.e., the platoons) are more affected by re-supply method.

- The CO trends related to risk, re-supply method, and ULS numbers are similar to the trends that appear in the GCE's partition tree. However, the GCE has an additional split relating to the LCE's initial DOS levels. This is the only occurrence of initial DOS levels within any of the partition trees.

The trends for the companies and GCE bear many similarities. The trends for the LCE differ from these two, yet are similar to the other units. Figure 19 shows the partition tree for the LCE.



The red box illustrates the branch that results in the highest re-supply rate.

Figure 19. LCE Partition Tree

The LCE shares similarities with the companies and the GCE in terms of the importance of medium and large ULSs numbers, but the LCE is more affected by the re-supply method. This is interesting because the LCE, independent of re-supply method, only receives supplies from the seabase via L-ULS. All units are in some way affected by the re-supply method. The number of L-ULSs at the SEA is the most important factor for successful re-supply of the LCE.

The trends annotated in Section B relate to risk, ULS numbers at varying units, and re-supply method. These trends are re-examined in Section 2 using boxplots.

2. Box plots

Box plots show relationships within data. For purposes of this research, box plots demonstrate the average percentage of successfully delivered supplies (i.e., the average of the amount of supplies received over the amount of supplies requested for each design point) or the number of lost ULSs, across risk levels and in relation to types of re-supply method. These box plots concentrate on the changes in risk and re-supply method because these factors have the greatest effects on successful re-supply. The importance of these factors, however, could also change depending on the unit, and the box plots assist in identifying trends.

a. Delivered Supplies, Risk, & Re-supply Method

Figure 20 shows a boxplot of the relationship between the amounts of successfully delivered supplies, risk, and re-supply method.

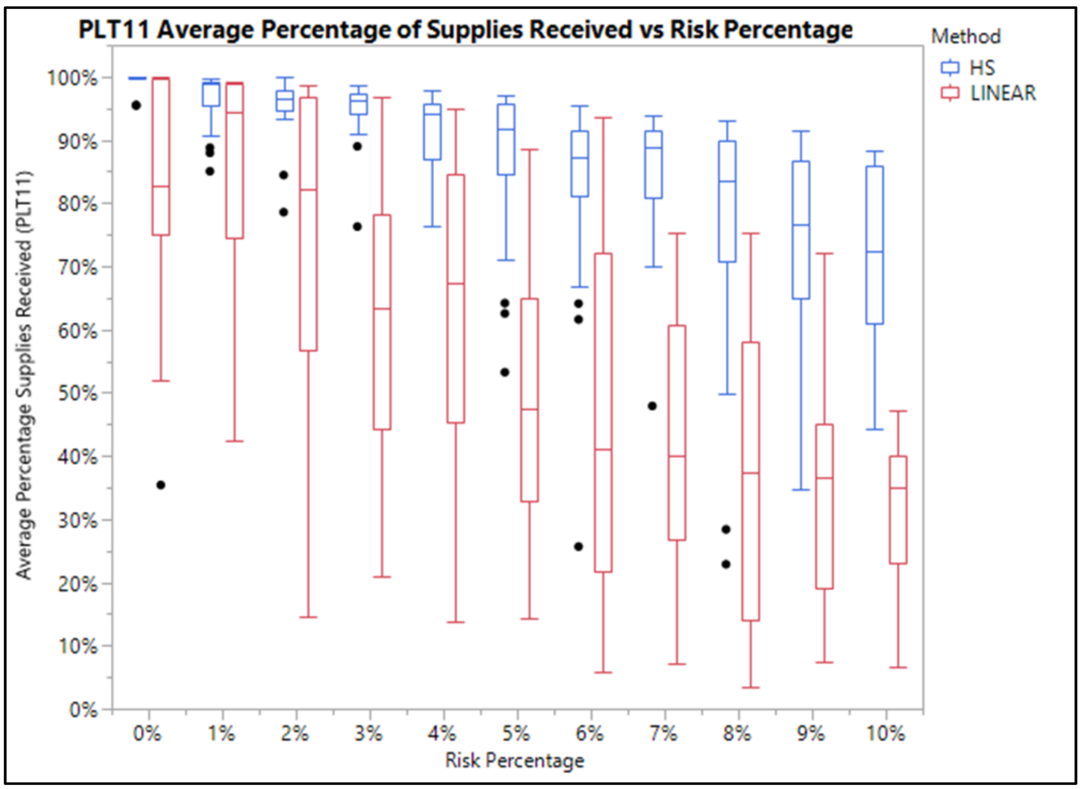


Figure 20. PLT11 Box Plot of the Average Amount of Supplies Received vs. Risk Percentage.

Figure 20 illustrates the importance of the re-supply method for PLT11, as well as the other platoons. At the platoon level, the hub-and-spoke re-supply method not only results in a higher percentage of successfully delivered supplies, but it also has less variability. This method also performs better independent of risk; it results in a higher percentage of successfully delivered supplies and is less variable at both a low and a high risk level. The plotted variability and outliers demonstrate the real-world chaos of logistics processes. While the hub-and-spoke method is clearly superior for PLT11, the re-supply methods are more similar for CO1. This can be seen in Figure 21.

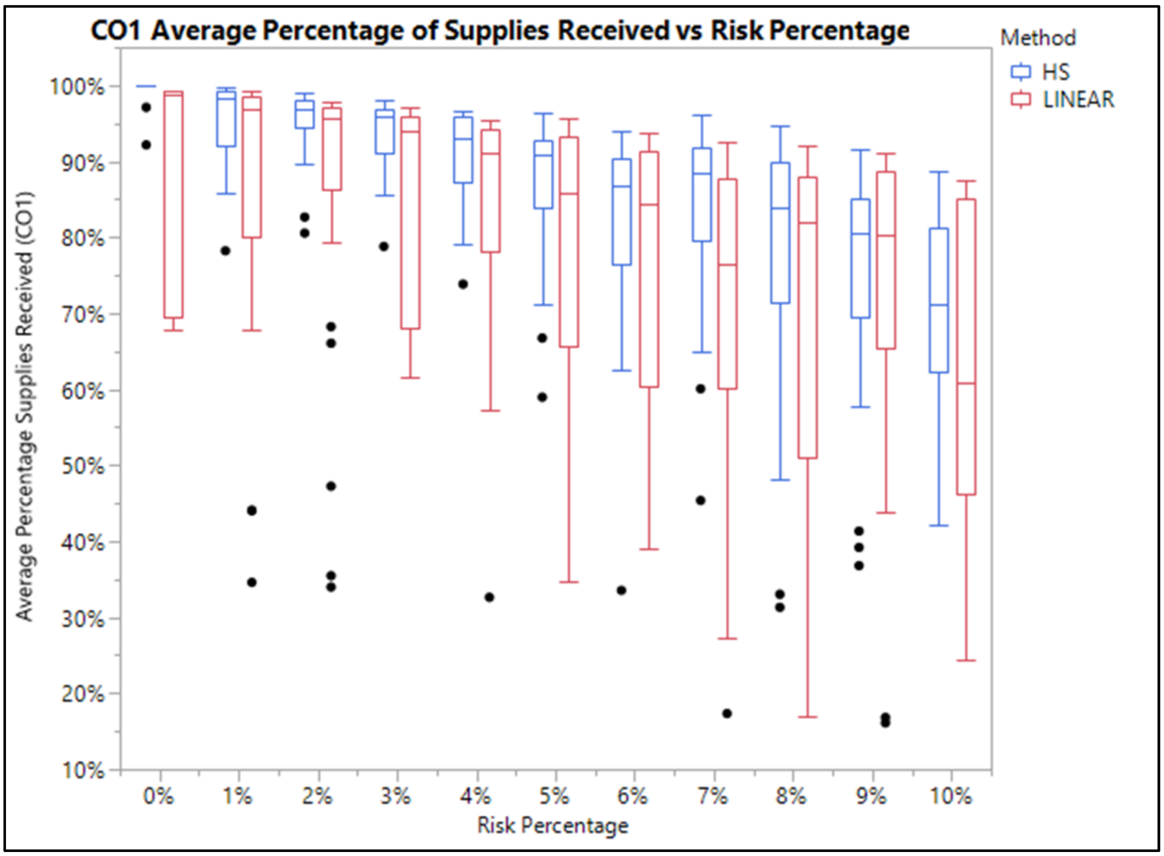


Figure 21. CO1 Box Plot of the Average Amount of Supplies Received vs. Risk Percentage

The methods of re-supply provide more similar results for CO1. At higher risks, the linear method has an on par or better average ratio, however the linear method's variability is still larger across all risk levels. This theme continues with the GCE as depicted in Figure 22.

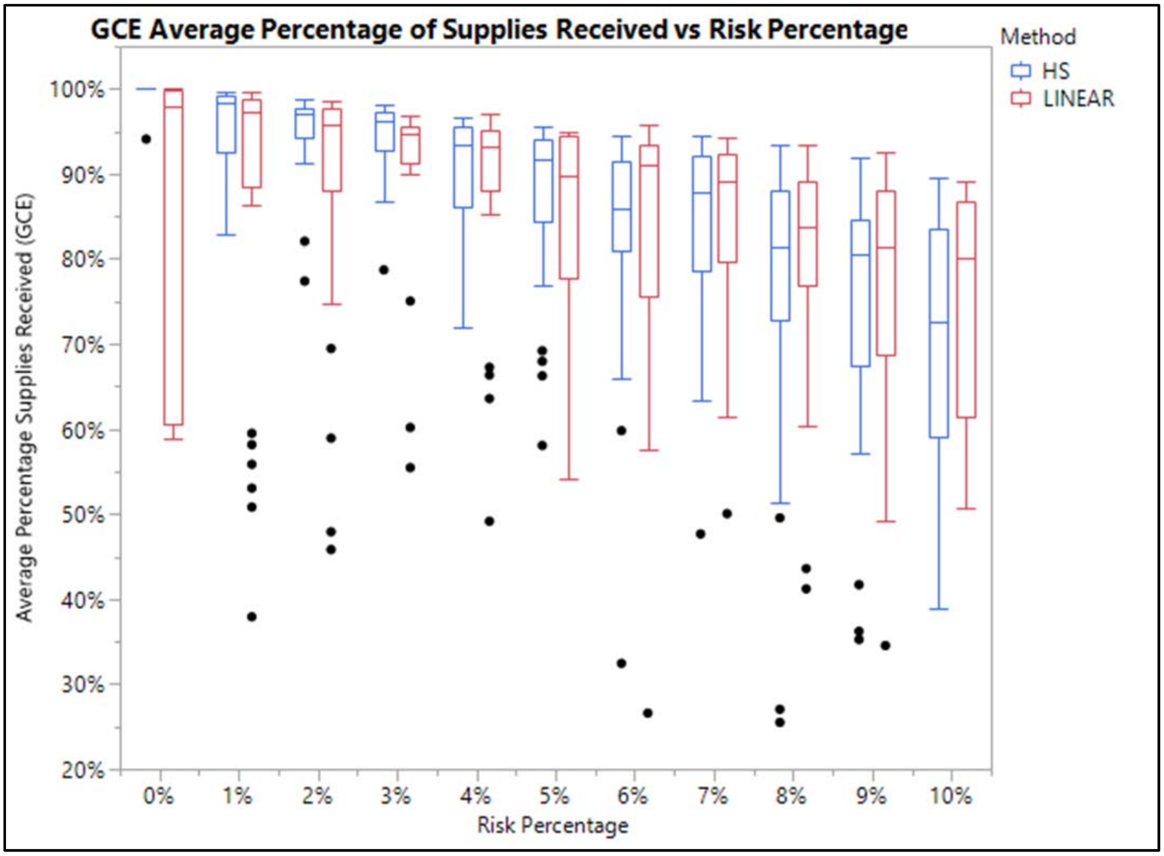


Figure 22. GCE Box Plot of the Average Amount of Supplies Received vs. Risk Percentage

As seen in Figure 22, and when compared to Figure 21, the amount of successfully delivered supplies at the GCE level is less affected by the re-supply method. The average amount of supplies and the variability are similar across risk levels. This similarity is again changed at the LCE level, visible in Figure 23.

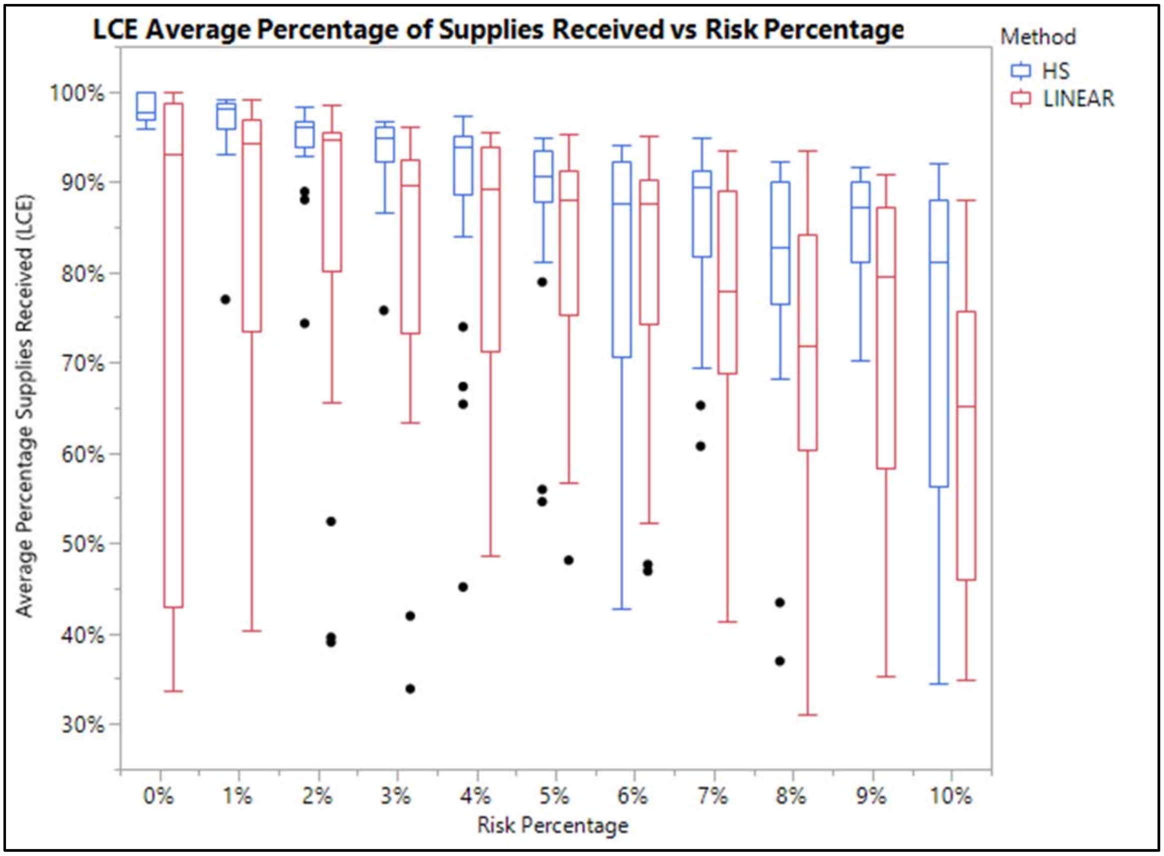


Figure 23. LCE Box Plot of the Average Amount of Supplies Received vs. Risk Percentage

The hub-and-spoke method has higher averages of successfully delivered supplies as well as lower variability across risk percentages when compared to the linear method. These results are more similar to the platoons than the companies or the GCE. When looking at trends across units, the farther away the unit is from the logistics hub (i.e., the LCE), the more its supply ratio is affected by the re-supply method. Figure 24 shows the averages for the entire system.

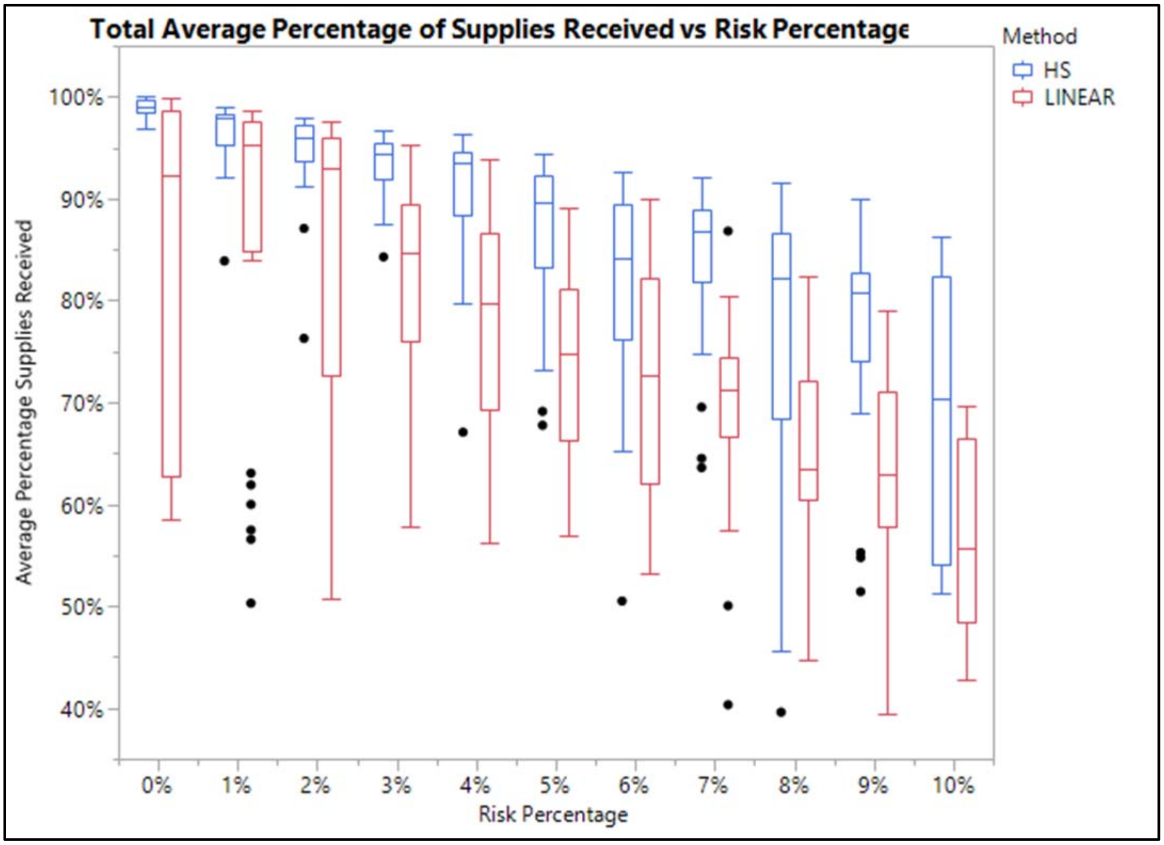


Figure 24. Box Plot of the Total Unit Average Amount of Supplies Received vs. Risk Percentage

Over the entire system, the hub-and-spoke method returned higher total average amounts of successfully delivered supplies, independent of risk levels. While the linear method has more variability at lower risk levels, the methods become comparable at higher risks.

While box plots show the relationship between the ratios of delivered supplies and re-supply methods across risk levels, they can also show the numbers of unit ULSs lost across levels of risk.

b. Lost ULSs, Risk, & Re-supply Method

Varying levels of risk not only affect the averages of supplies successfully delivered to units, but also affects the number of ULSs that are lost in the scenario. These loss numbers differ by unit and also relate to the re-supply method.

CO1 and the GCE both possess S-ULSs which are used for re-supply only during the linear method. The loss averages for these units can be seen in Figure 25.

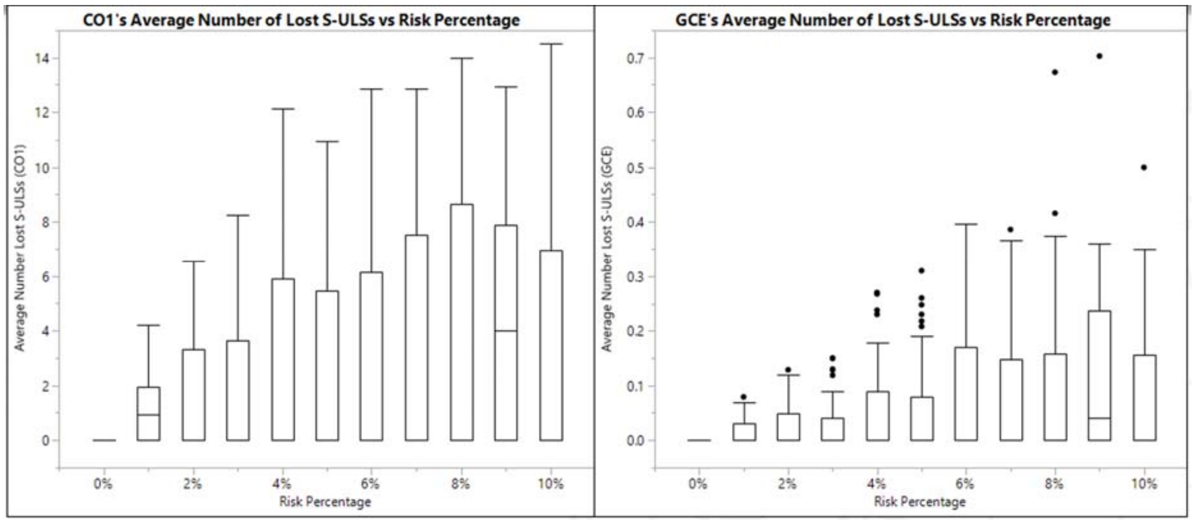


Figure 25. CO1 and GCE S-ULSs Lost Across Risk Percentages.

The loss of S-ULSs at the company and GCE level show that the average loss number does not consistently increase along with risk percentage. The peak risk for both units occurs at 9%, but after 6% both units experience variations of loss numbers. This behavior also occurs at the LCE level as seen in Figure 26.

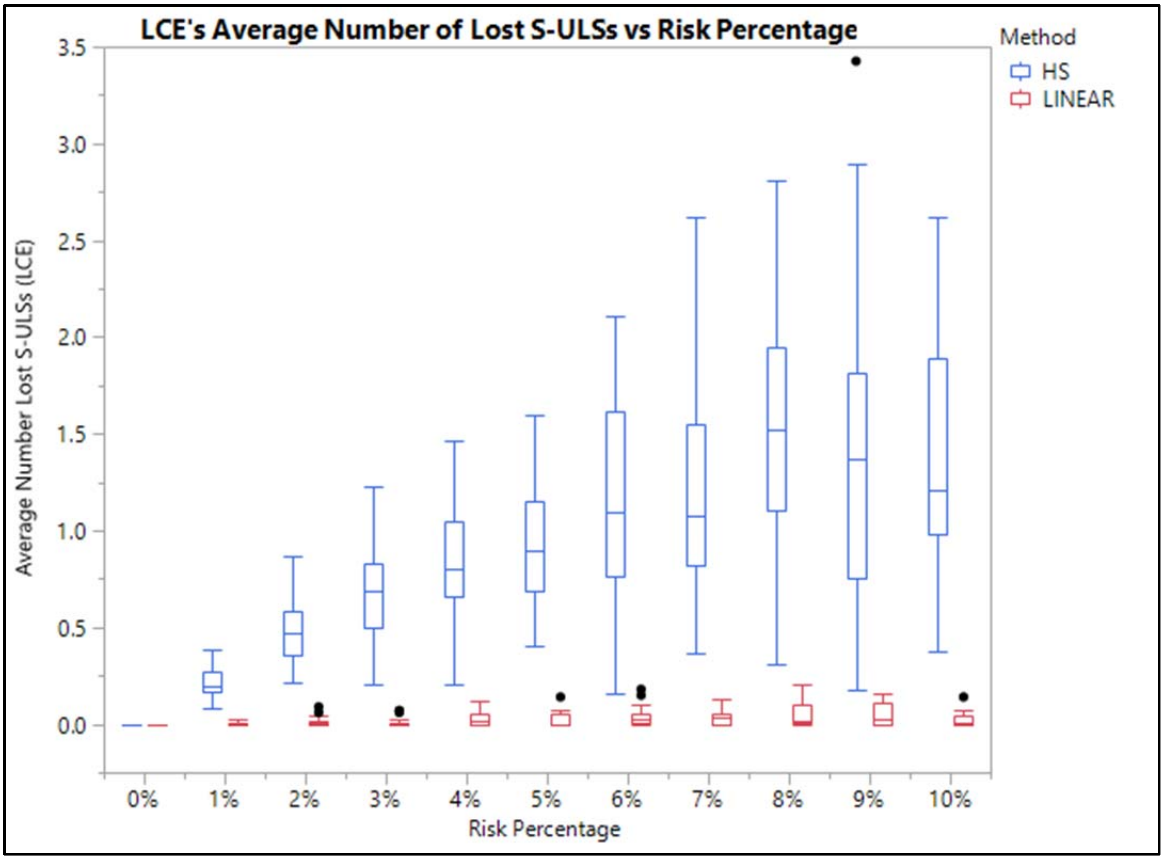


Figure 26. LCE S-ULS Lost Across Risk Percentage.

Like CO1 and the GCE, the LCE's S-ULS loss numbers do not consistently rise with the risk percentage, rather, 6 - 10% risk is variable with a peak loss at 8%. Of note, the difference between the loss numbers relating to the re-supply method occur because the LCE performs most of the logistic re-supply for the hub-and-spoke method. Because the LCE uses more ULSs when using the hub-and-spoke, they concurrently lose more ULSs.

The GCE's losses of M-ULSs appear to be similar to their loss numbers for the S-ULSs. This can be seen in Figure 27 and when compared to Figure 25, the variability of losses and peak losses occur at similar risk percentages for the GCE's small and medium ULSs.

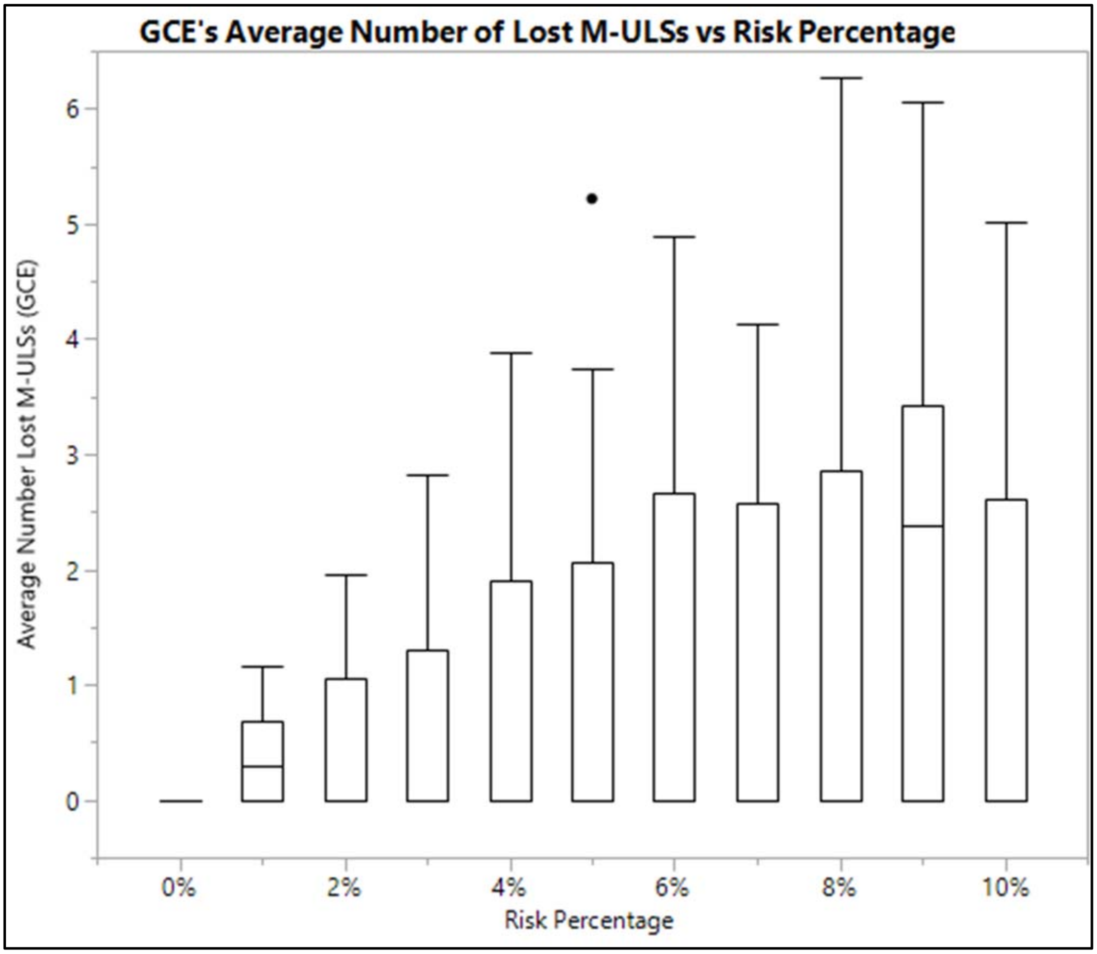


Figure 27. GCE M-ULSs Lost Across Risk Percentage

Figure 28 depicts the LCE's lost M-ULS. The results depict loss rates for both the linear and hub-and-spoke method.

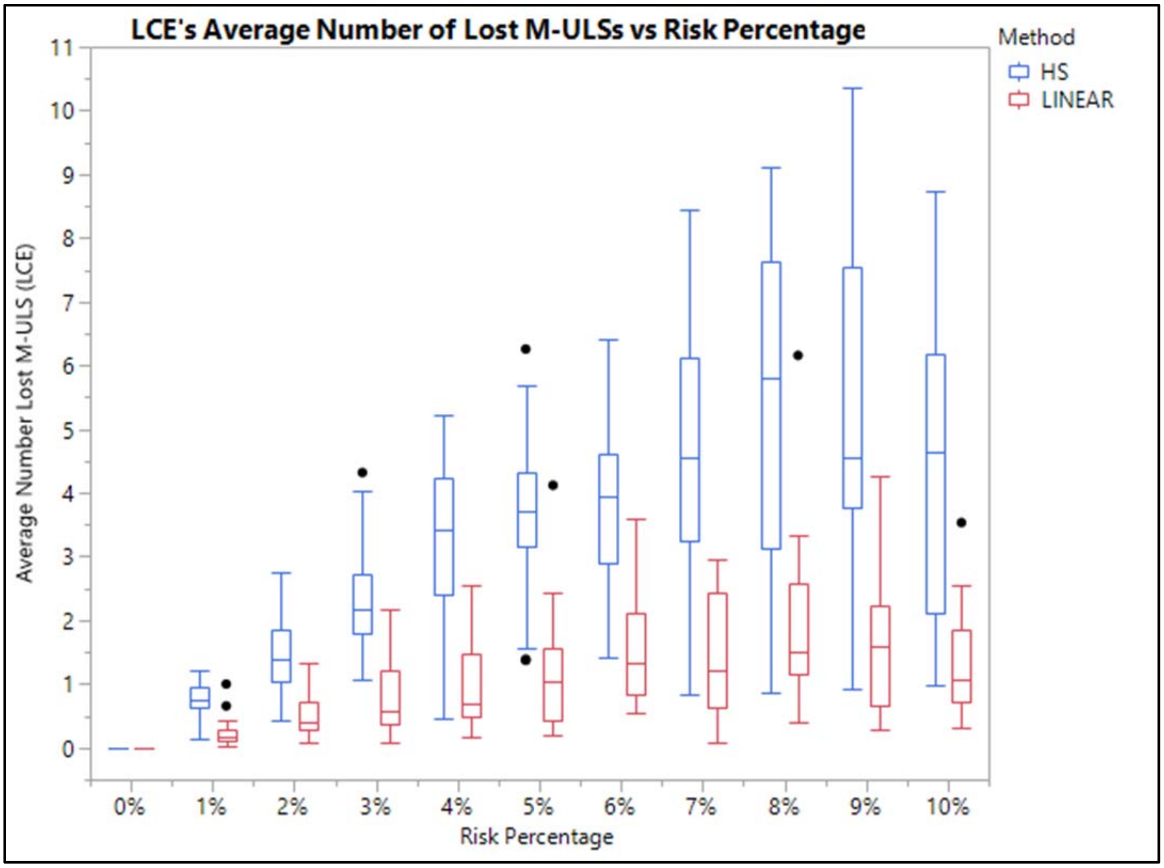


Figure 28. LCE M-ULSs Lost Across Risk Percentage

Figure 28 is similar to Figure 26, the loss rates for the LCE's S-ULS, because the LCE uses more and loses more ULSs in the hub-and-spoke method. This figure shows a peak loss at 8% and larger loss number variability at higher risks. L-ULS loses at the LCE and SEA level are shown in Figure 29.

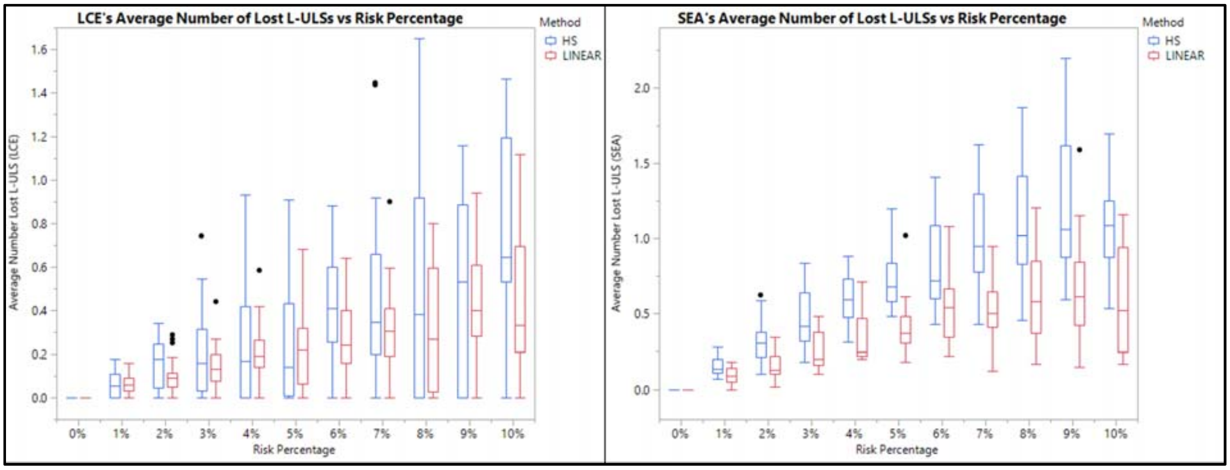


Figure 29. LCE and SEA L-ULSs Lost Across Risk Percentage

Figure 29 shows more similarities between methods in terms of ULSs lost.

There are trends across all units in terms of numbers of ULSs lost. At higher risk levels (i.e., > 6%), ULSs are not lost correspondingly with increasing risk percentages, and the peak risk most often occurs at 8 or 9%. This shows that survivability improvements to systems, improvements that decrease risk, should not be treated equally. For example, attempts to reduce system risk from 10% to 8% would provide marginal benefits as the difference in losses between the two is negligible. However, if risk could instead be reduced to 4%, then the return on investment would merit dedication of resources to the reduction of risk. This is because the risk is not uniformly distributed and instead appears to be broken up into risk tiers. Lowering risk would not necessarily decrease the number of ULSs lost unless the risk was lowered enough to get out of a specific risk tier.

3. Regressions

Regressions further illuminate the relationship between the predictors (i.e., input ranges or factors for the simulation) and the desired response. These regressions are specifically stepwise regressions, and are run with factors, interactions, and second degree polynomials. The stepwise regression allows for flexibility when adding model predictors and the ability to remove effects that are determined to be unimportant. The most illustrative regression is for the platoon level. Figure 30 shows PLT11's actual response as compared to the predicted response.

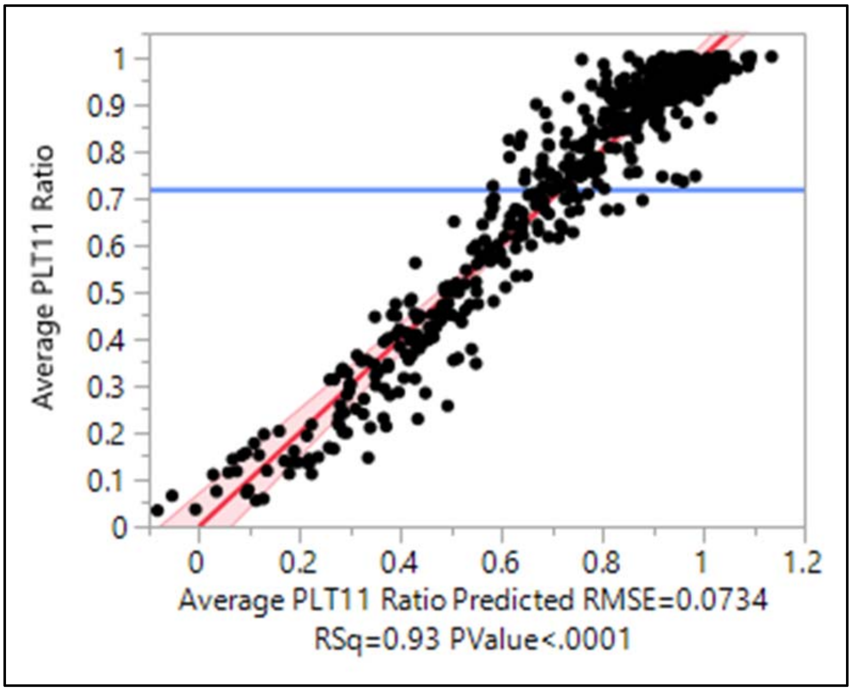
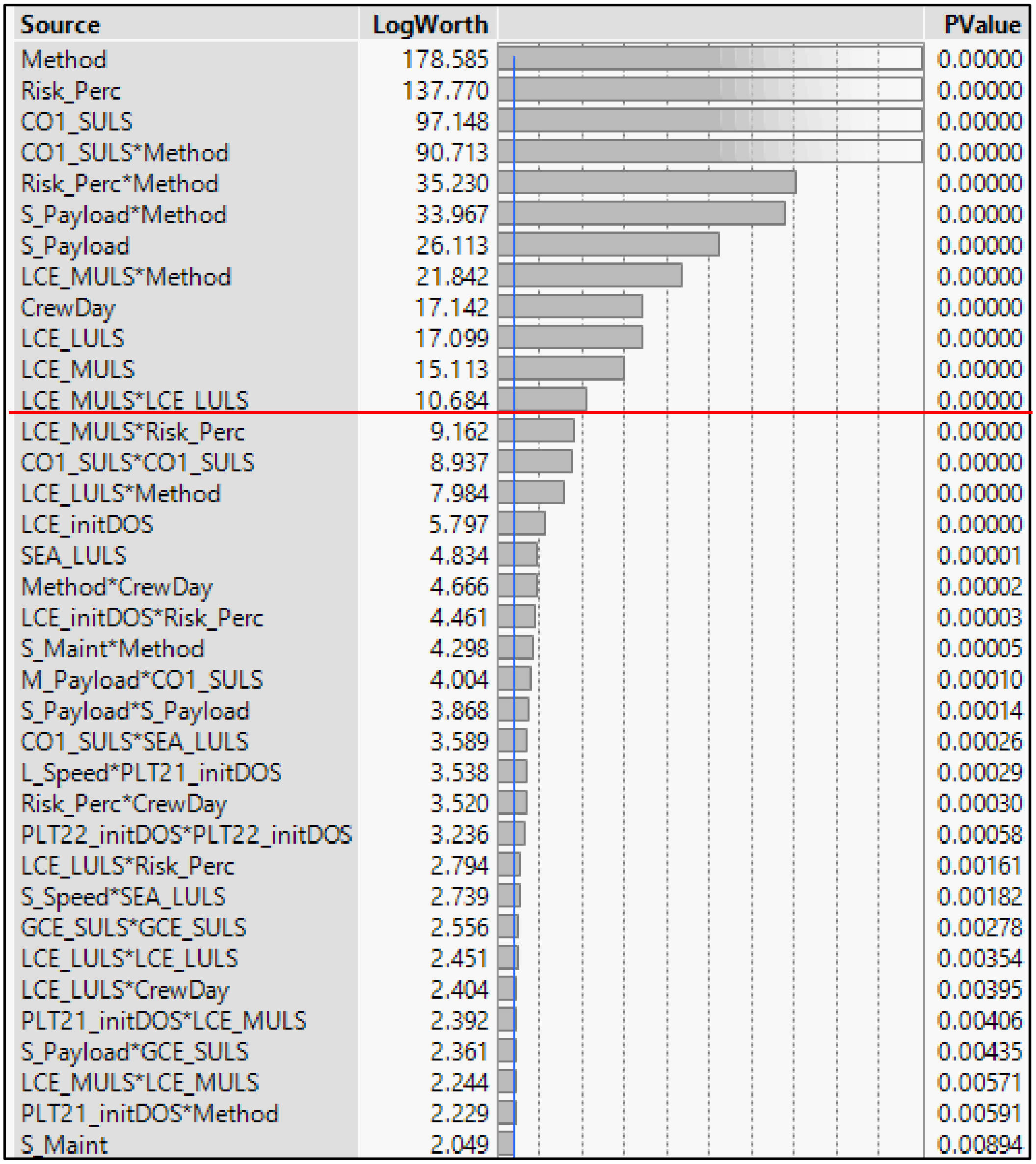


Figure 30. PLT11 Regression—Actual vs. Predicted Response

For the chaotic and random system that is a logistics system, the values in Figure 30 appear to follow a linear pattern. This shows that the regression model is fairly good at predicting PLT11's average ratio of successfully delivered supplies. The regression also illuminates what factors are influential in the model. Because there are 32 different factors, their interactions, and second degree polynomials, the regression sifts through many predictors for those predictors that have a significant effect on the regression response. The final regression's effect summary details the significant factors and can be seen in Figure 31. This figure does not show all of the effects that comprise the final regression model; effects with less significance comparatively, are not included.



Source	LogWorth	PValue
Method	178.585	0.00000
Risk_Perc	137.770	0.00000
CO1_SULS	97.148	0.00000
CO1_SULS*Method	90.713	0.00000
Risk_Perc*Method	35.230	0.00000
S_Payload*Method	33.967	0.00000
S_Payload	26.113	0.00000
LCE_MULS*Method	21.842	0.00000
CrewDay	17.142	0.00000
LCE_LULS	17.099	0.00000
LCE_MULS	15.113	0.00000
LCE_MULS*LCE_LULS	10.684	0.00000
LCE_MULS*Risk_Perc	9.162	0.00000
CO1_SULS*CO1_SULS	8.937	0.00000
LCE_LULS*Method	7.984	0.00000
LCE_initDOS	5.797	0.00000
SEA_LULS	4.834	0.00001
Method*CrewDay	4.666	0.00002
LCE_initDOS*Risk_Perc	4.461	0.00003
S_Maint*Method	4.298	0.00005
M_Payload*CO1_SULS	4.004	0.00010
S_Payload*S_Payload	3.868	0.00014
CO1_SULS*SEA_LULS	3.589	0.00026
L_Speed*PLT21_initDOS	3.538	0.00029
Risk_Perc*CrewDay	3.520	0.00030
PLT22_initDOS*PLT22_initDOS	3.236	0.00058
LCE_LULS*Risk_Perc	2.794	0.00161
S_Speed*SEA_LULS	2.739	0.00182
GCE_SULS*GCE_SULS	2.556	0.00278
LCE_LULS*LCE_LULS	2.451	0.00354
LCE_LULS*CrewDay	2.404	0.00395
PLT21_initDOS*LCE_MULS	2.392	0.00406
S_Payload*GCE_SULS	2.361	0.00435
LCE_MULS*LCE_MULS	2.244	0.00571
PLT21_initDOS*Method	2.229	0.00591
S_Maint	2.049	0.00894

Figure 31. PLT11 Regression Effects Summary

While there are a number of significant factors in the model, the factors at the top of the list in Figure 31 reinforce the analysis from the partition trees and box plots. The method of re-supply, risk levels, and number of company level S-ULSs continue to be important in the prediction of the average amount of supplies that are successfully delivered. Analysis of the regression, however, also reveals that interactions are important. These model coefficients can be used to predict the amount of supplies delivered to PLT11 but there are a total of 44 coefficients, making the equation slightly unwieldly. To create a simpler model, all the predictors below the red line in Figure 31 are removed. With this simpler model, the R^2 reduces to 0.88 with 12 terms.

Regressions also offer insights into the total average amount of supplies delivered throughout the logistics process. The actual vs. predicted values for the total amount of supplies can be seen in Figure 32.

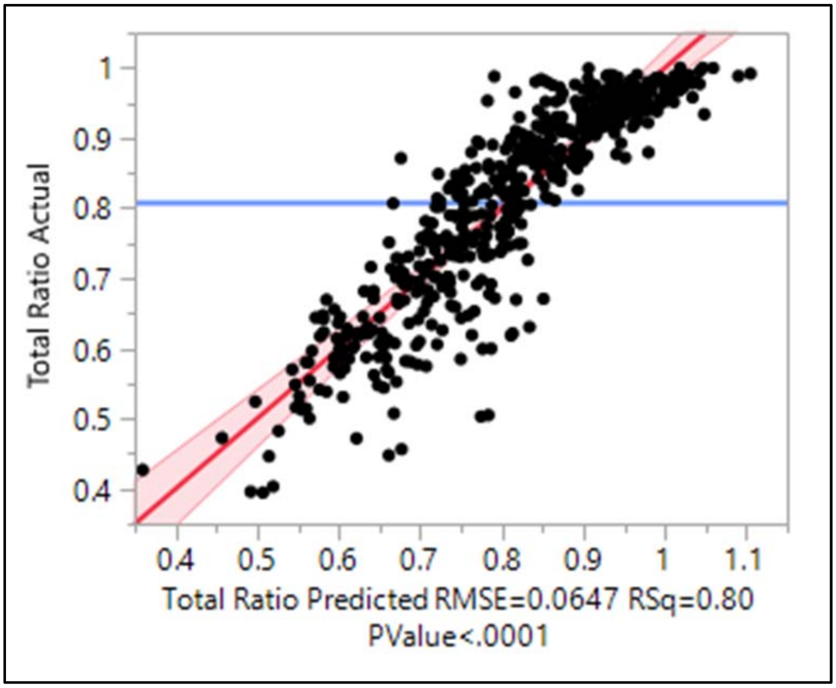


Figure 32. Totals Regression—Actual vs. Predicted Plot.

When compared to Figure 30, Figure 32's model for the total amount of supplies successfully delivered is not as good of a fit. The R-squared is lower and the predicted values, the black dots, are farther away from the actual values depicted by the red line. There are also fewer significant factors in the regression for the total average percentage of supplies delivered, making the model simpler to use than the PLT11 regression model. These significant factors can be seen in Figure 33.

Source	LogWorth	PValue
Risk_Perc	101.094	0.00000
Method	65.822	0.00000
GCE_MULS*Method	17.784	0.00000
GCE_MULS	15.261	0.00000
LCE_MULS*LCE_LULS	14.748	0.00000
LCE_MULS	13.930	0.00000
SEA_LULS	12.855	0.00000
LCE_initDOS	11.942	0.00000
LCE_initDOS*Method	10.316	0.00000
CrewDay	9.857	0.00000
SEA_LULS*SEA_LULS	7.828	0.00000
LCE_MULS*Risk_Perc	7.178	0.00000
LCE_LULS	6.593	0.00000
LCE_initDOS*Risk_Perc	6.422	0.00000
GCE_MULS*GCE_MULS	6.153	0.00000
LCE_initDOS*LCE_initDOS	5.927	0.00000
SEA_LULS*Method	5.164	0.00001
LCE_MULS*Method	3.909	0.00012
SEA_LULS*Risk_Perc	2.935	0.00116
CO2_SULS*GCE_MULS	2.821	0.00151
Risk_Perc*CrewDay	2.659	0.00219
CO2_SULS	1.142	0.07208

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.6351017	0.02402	26.44	<.0001*
CO2_SULS	0.0012756	0.000708	1.80	0.0721
GCE_MULS	0.0091976	0.001097	8.38	<.0001*
LCE_initDOS	0.022027	0.003016	7.30	<.0001*
LCE_MULS	0.0056843	0.000714	7.96	<.0001*
LCE_LULS	0.0158278	0.003028	5.23	<.0001*
SEA_LULS	0.0179471	0.002358	7.61	<.0001*
Risk_Perc	-2.760533	0.099993	-27.61	<.0001*
Method[HS]	0.05832	0.002883	20.23	<.0001*
CrewDay	0.0047245	0.00072	6.56	<.0001*
(CO2_SULS-8)*(GCE_MULS-5.5)	0.0008571	0.000269	3.19	0.0015*
(GCE_MULS-5.5)*Method[HS]	-0.0101	0.001105	-9.14	<.0001*
(LCE_initDOS-3.5)*(Risk_Perc-0.05)	-0.521049	0.101173	-5.15	<.0001*
(LCE_initDOS-3.5)*Method[HS]	-0.020252	0.00301	-6.73	<.0001*
(LCE_MULS-8)*(LCE_LULS-1.5)	-0.006093	0.000741	-8.22	<.0001*
(LCE_MULS-8)*(Risk_Perc-0.05)	0.1339752	0.024425	5.49	<.0001*
(LCE_MULS-8)*Method[HS]	0.0027489	0.00071	3.87	0.0001*
(SEA_LULS-3)*(Risk_Perc-0.05)	0.2631697	0.080544	3.27	0.0012*
(SEA_LULS-3)*Method[HS]	0.01076	0.002366	4.55	<.0001*
(Risk_Perc-0.05)*(CrewDay-20.1563)	0.0769225	0.02498	3.08	0.0022*
(GCE_MULS-5.5)*(GCE_MULS-5.5)	-0.002276	0.000453	-5.03	<.0001*
(LCE_initDOS-3.5)*(LCE_initDOS-3.5)	-0.015291	0.003108	-4.92	<.0001*
(SEA_LULS-3)*(SEA_LULS-3)	-0.01114	0.001934	-5.76	<.0001*

Figure 33. Total Regression Summary

As depicted in Figure 33, the source column shows, in order of significance, the coefficients that affect the model. Risk and re-supply method, as well as the ULS numbers are the most significant factors. LCE assets and both medium and large ULSs, also appear. This result is consistent with the importance of medium and large ULSs in the hub-and-spoke method. If using the model for prediction, the values in the term and estimate column in Figure 33 can be used to calculate the total amount of supplies delivered in the process.

Partition trees, box plots depicting data relationships, and regressions illustrate the trends that are present in the data. These trends can inform the development of concepts of operation and employment for ULSs in support of distributed operations.

B. SECOND SCENARIO - NOB DESIGN OVERVIEW

The main NOB design runs ranges of inputs to illuminate significant factors in relation to specific responses (i.e., percentage of successfully delivered supplies). The analysis using partition trees, box plots, and regressions not only shows what factors are important, but shows the point within a factor range when re-supply success gets better or worse. (i.e., the partition tree for PLT11 shows that if resupplying via the hub-and-spoke method, the percentage of successfully delivered supplies increases if the LCE possesses more than five M-ULSs). By examining the results from Section A, a smaller scenario is developed based on the employment and number of ULSs that could be operated. This smaller scenario demonstrates a specific logistics plan, the mix of small, medium, and large ULS that could be employed, and the amounts of supplies that are transported.

1. Inputs

Most of the scenario inputs are averages of the inputs for the main scenario, because the focus of this scenario is the number of LCE M-ULS and risk level. The number of unit personnel as detailed in Table 6 do not change for this scenario. Additionally, initial DOS and ROP for the SEA do not change, while all other unit's initial DOS and ROP both change to 2. The unit distances remain as depicted in Table 7. Table 9 depicts the data used for the ULS specifications. Because the specifications are not significant to successful re-supply, the inputs are averages of the main scenario, and are not a focus of this scenario.

Table 9. Second Scenario Inputs for the ULSs.

ULS Capability Factors	
Small ULS	
Payload Weight (lbs)	55
Speed (km/hr)	55
Load Time (min)	2
Maintenance Time (min)	5
Medium ULS	
Payload Weight (lbs)	600
Speed (km/hr)	100
Load Time (min)	10
Maintenance Time (min)	60
Large ULS	
Payload Weight (lbs)	4000
Speed (km/hr)	250
Load Time (min)	50
Maintenance Time (min)	100

The re-supply method is the hub-and-spoke method and the crew day is 16 hours. Risk level is varied at 0%, 4% and 8%. The LCE and SEA are the only units that possess ULSs. ULS number for the LCE and SEA are detailed in Table 10.

Table 10. Second Scenario LCE and SEA ULS Numbers

Available ULSs per Unit			
	ULS Numbers		
Unit	Small ULS	Med. ULS	Large ULS
SEA	0	0	2
LCE	2	5, 8, 11, 14	0

There are a total of 12 input variations due to the changing risk levels and the number of the LCE's M-ULSs. Each input is run 300 times for a total of 3,600 output files.

2. Results

Every unit has a result based on each risk and the number of LCE M-ULSs. These results depict the average percentage of successfully delivered supplies using four different quantities of M-ULSs. Figure 34 shows the average percentage of successfully delivered supplies for PLT11, and the relationship to risk levels and the number of M-ULSs the LCE operates. There is some linear interpolation contained in this graph, as well as in Figures 35–36, due to these simulation inputs (i.e., the simulation was run with 5 M-ULSs but not 6, so for graphing purposes, results for 6 are linearly interpolated).

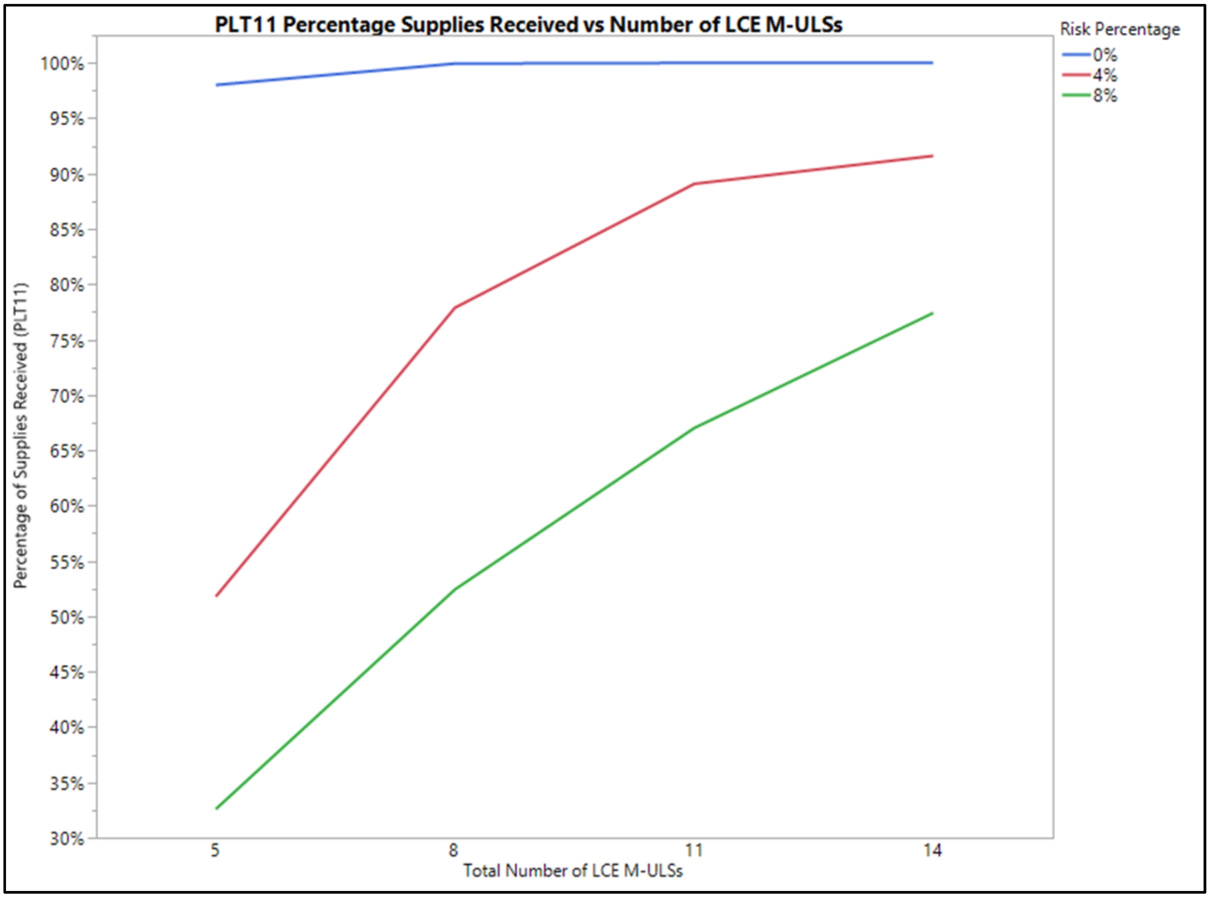


Figure 34. PLT11 Average Percentage of Supplies Received Based on Risk Levels and the Number of LCE M-ULSs

As seen in Figure 34, risk level has a substantial effect on the overall percentage of successfully delivered supplies. Without risk, there can be anywhere from 5 to 14 ULSs that are able to complete the re-supply. However, at 4% risk and 8% risk, the amount of successfully delivered supplies drops. This figure also shows that the number of LCE M-ULSs does not directly correlate with successful re-supply. For 4% risk, success rapidly increases until the LCE is operating with 8 M-ULSs, slows re-supply improvement from 8 to 11 M-ULSs and then only marginally improves with any additional M-ULSs. A “bend in the curve” also appears at 8 in the 8% risk category, however, the percentage of successfully delivered supplies continues to climb with the number of operational M-ULSs. This illustrates that for this scenario, with 4% risk, there is only marginal improvement with any additional M-ULSs over 11, but the higher risk would need even greater M-ULS numbers to overcome scenario risk. Deploying 8 or 11 M-ULSs at the LCE, dependent on risk and how many M-ULS is it acceptable to lose in exchange for increases in average re-supply percentage, has the most benefit for successful re-supply in this scenario. To put the supply percentages in perspective, complete success would mean that the ULSs were able to deliver all MRE and drinking water requirements for the 6 day operation. Another way to look at risk across LCE M-ULS numbers and risk is seen in Figure 35.

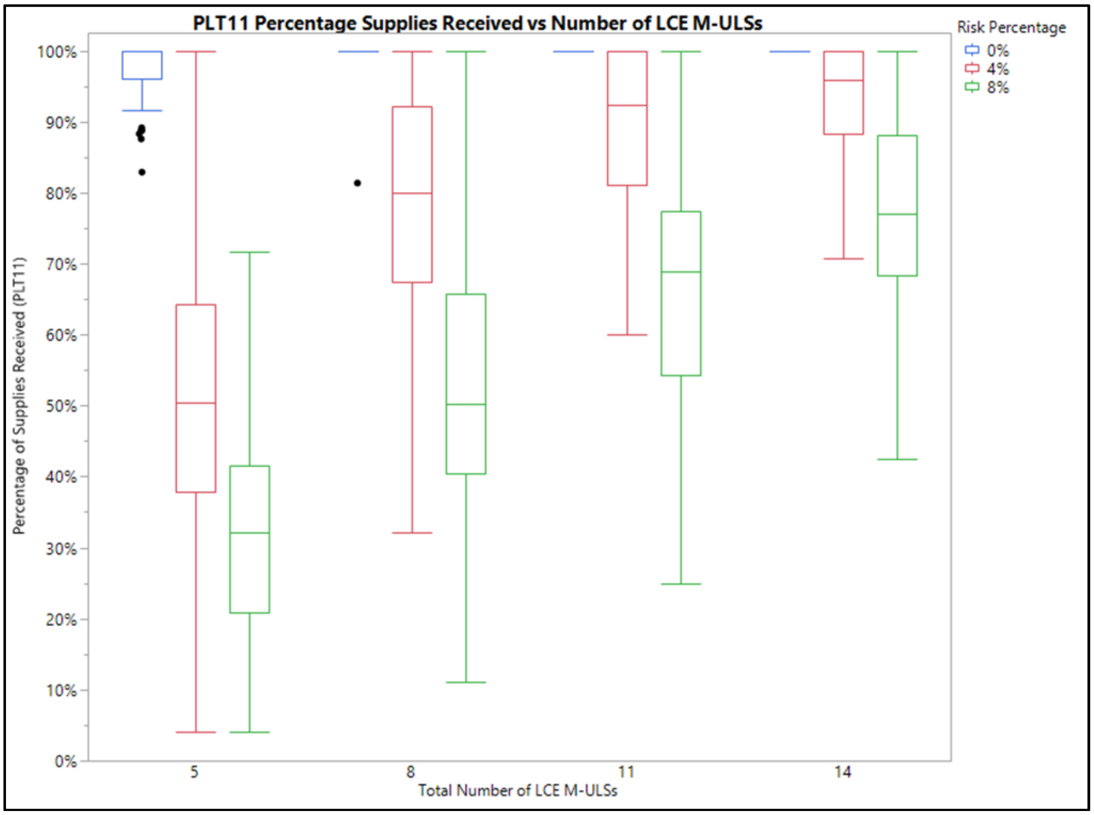


Figure 35. PLT11 Percentage of Supplies Received based on Risk Levels and the Number of LCE M-ULSs (Box Plot)

Using all 3,600 output data points, Figure 35 illustrates the ranges in successfully delivered supplies. As LCE M-ULSs numbers rise, the effects of risk (i.e., system variability) goes down as a result.

In addition to successfully delivered supplies, the second measure of effectiveness for the system is the number of ULSs lost based on scenario. Figure 37 illustrates the average number of the LCE's M-ULS lost when compared to risk level and the total number of systems in operations.

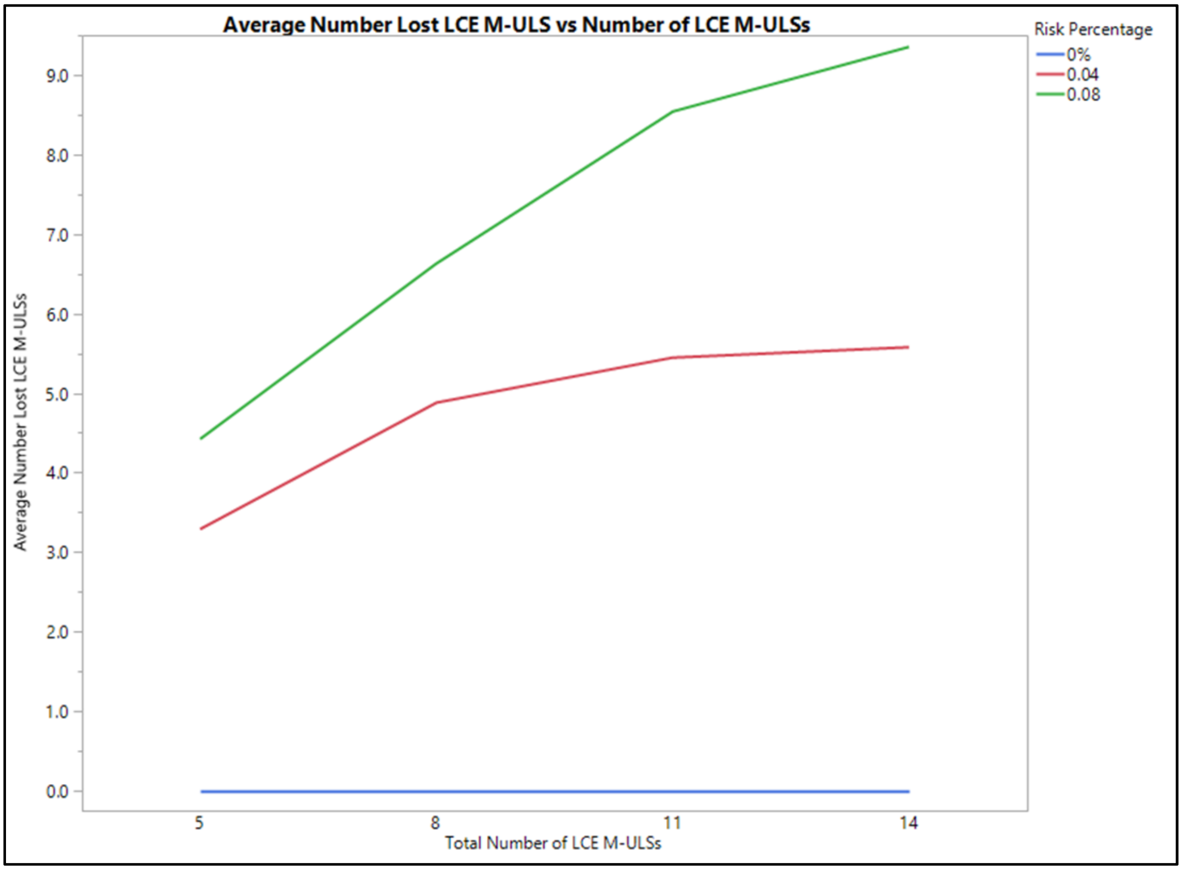
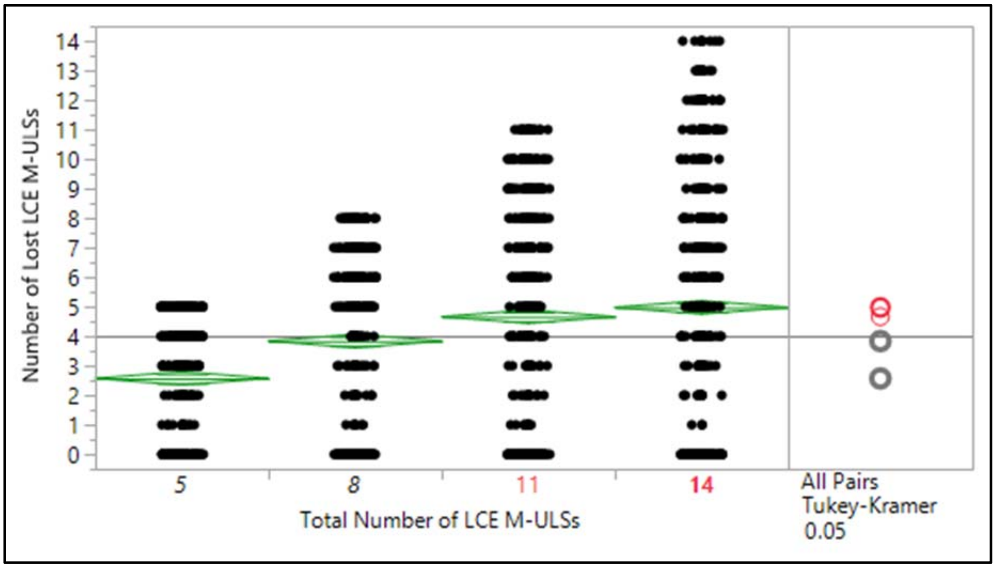


Figure 36. Average Number of LCE M-ULSs Lost vs.
Total Number of LCE M-ULSs

As expected, ULSs are not lost when there is no risk. At 4% risk, there is an increase in lost M-ULSs across the range of ULSs from 5 to 11. After 11 total ULSs there is an only a marginal increase in lost M-ULSs. At 8% risk, however, the risk to ULSs is still rising at a noticeable rate when more than 11 ULSs are operating.

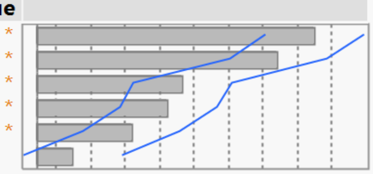
The average number of LCE M-ULSs that are lost, as compared with the total number of LCE M-ULSs, can be illustrated in other ways. Figure 37 and 38 show there is not a statistically significant difference between having 11 or 14 total M-ULSs. Even if the observed difference was statistically significant, the difference is relatively small and not likely to be of practical importance.



The green diamonds show the mean lost M-ULSs per total number of M-ULSs. When the total number of LCE M-ULS is 11 or 14, the means are nearly the same. The circles on the right side correspond to a total number of LCE M-ULSs. The red overlapping circles show the totals of 11 and 14, and that they are not significantly different. Also of note, for all four factor settings, there are cases where all of the M-ULSs were lost.

Figure 37. One-way Analysis of Lost LCE M-ULSs By Total Number of LCE M-ULSs

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
14	5	2.405556	0.1640606	1.98388	2.827230	<.0001*
11	5	2.091111	0.1640606	1.66944	2.512785	<.0001*
8	5	1.265556	0.1640606	0.84388	1.687230	<.0001*
14	8	1.140000	0.1640606	0.71833	1.561674	<.0001*
11	8	0.825556	0.1640606	0.40388	1.247230	<.0001*
14	11	0.314444	0.1640606	-0.10723	0.736118	0.2211



The p-values show that all of the combinations of total number of LCE M-ULSs are significantly different except the last; the combination of 11 and 14 is not significantly different.

Figure 38. Ordered Difference of LCE M-ULSs

This analysis provides insights about the number of ULS that should be employed, and illustrates that certain numbers of M-ULSs ultimately re-supply the similar percentages of supply. For this scenario, 11 ULSs should be employed because it minimizes lost M-ULSs while still successfully delivering 90% of supplies. While only applicable to this specific scenario, this model could be re-run with modified inputs to determine how many ULSs would be most beneficial for mission success based on the risk level that is willing to be assumed.

While the simulation itself is a useful tool, it becomes even more valuable when used in combination with data farming wrappers (see Sanchez and Sanchez 2017 for a general discussion). These wrappers enable the simulation to be run multiple times with different inputs, with as many replications as desired. Instead of manually running the simulation for every input, the user can specify multiple inputs, along with the number of replications, and the results are packaged in a single file. Simulating multiple replications of input ranges enables analysts to create a robust design modeling multiple scenarios. Because of this, sensitivity analysis is simplified.

The results of this study augment OAD’s analysis by examining ranges of capabilities in a more robust decision space. OAD’s findings in combination with this research, illustrate the benefits of ULS employment and shape their concept of operations.

V. CONCLUSION AND THESIS CONTINUATION

Marine Corps logistic support systems must be responsive, flexible, and sustainable if they are to successfully support highly maneuverable units, dispersed over large operational areas. ULSs have the potential to reduce Marine personnel risk and workload, while increasing throughput, efficiency, and flexibility in logistics processes.

A. CONCLUSIONS

In an attempt to influence the concept of operation and the concept of employment for future Marine Corps ULSs, this thesis used a discrete event simulation and a designed experiment to model a ship-to-shore logistics process in a dispersed operation. The simulation output was analyzed and trends are as follows:

- Out of the factors that can be controlled, ULS employment method is more important than ULS specifications, number of systems, or any other factor, in predicting successful re-supply. The hub-and-spoke method demonstrates less variability across most design points, returns higher ratios of successfully delivered supplies, and performs better at both high and low risk than the linear method of distribution.

- The number of medium and large ULSs are important factors for most of the Marine units while the specific ULS characteristics (e.g., payload, speed) are much less important. This implies that the quantity of ULSs employed matters more than the ULS capability specifications. From an acquisitions perspective, this result illustrates that having a “70% solution” for a ULS platform is good enough. The system does not have to be comprised of an exacting set of specifications because overall, achieving the perfect set of specifications has a limited effect on the effectiveness of the ULS re-supply system. Developing a cost-effective and “good enough” ULS that could be procured in large quantities and employed extensively, would have a larger effect on the efficiency of conducting distributed logistics operations than would the development of the perfect ULS.

- The farther a unit is from the main logistics node, the greater the effect of the re-supply method on high ratios of re-supply. If the platoon is the farthest entity away from the main units and is the “most important” by virtue of being the first to engage the enemy, employment of the hub-and spoke method rather than the linear method, benefits them the most.

- S-ULSs should be employed for just-in-time logistics (i.e., rapid delivery of small loads), because S-ULS quantity did not appear as an important factor, other than at the platoon level. (The S-ULS was only significant at the platoon level because the company resupplied them only via S-ULSs when operating based on the linear method.) Because of their relative un-importance in the overall supply ratios for units, they should not be used for throughput operations. If the S-ULSs merely fulfills a just-in-time mission, there need not be a large procurement requirement for the system.

- In contrast to the S-ULS, the quantity of M-ULS employed was a significant factor at nearly every Marine unit level, and therefore should be used for throughput functions (given the availability of small and larger ULSs, M-ULS are preferred). The M-ULS platform should be the primary focus when conducting ULS throughput operations.

- The logistics process is inherently complicated and chaotic. This makes it hard to control and even harder to predict. Variability within the system, however, can be mitigated. Risk is a significant factor in the simulation and this analysis shows that the mitigation of this risk is a large predictor of re-supply success. Employing a survivable and reliable system is important in mitigating this risk. Additionally, spreading out the risk among multiple M-ULSs instead of one L-ULS reduces the impact of losing a system and payload.

- The second scenario, using the hub-and-spoke method during 16 hour crew days and moving 55 lbs worth of DOS (i.e., a "best use" scenario), is an illustration of how the model can be used to explore risk based on specified scenario inputs. The recommended number of M-ULSs at the LCE level should be determined based on the analysis output and dependent on the amount of risk a commander is willing to assume. In this case the number of M-ULSs at the LCE should be 11 to balance the trade-offs between lost ULSs and logistics throughput.

- While this research did not look at command and control systems, in order to have sustainment visibility at all levels, the logistician would need to leverage a robust command and control architecture to effectively employ ULS re-supply systems.

- The methods used in this study can serve as a template for future work. Modeling a logistics process with different re-supply transportation is a cheap and easy way to gain insight about a system. While this research concentrated more on overall system processes, it would be advantageous to also look at more detailed information. Once a ULS has been procured, this model could be re-run with those ULS specifications.

B. CONTINUATION

Future work regarding ULS employment and operation includes:

- Continuing simulation work. Once the Marine Corps has a procured ULS, the ULS's specific capability set can be run in the model. The data collected from running the model with real-world specifications would inform decisions such as how many ULSs should be assigned to each Marine unit at varying levels in the tactical theatre.

- Additional scenarios, units, re-supply methods, transportations types, and supply classes could be added to the model.

- This work could be used to create a planning tool that optimizes logistics re-supply using all assets available (i.e., ground transportation, air assets, and ULSs).

- A detailed analysis could determine what assets in the Marine Corps' inventory could be replaced in favor of the ULS. This could include looking at tables of organization and equipment, training requirements, and replacement and operating costs.

- The design of a command and control infrastructure that meets the requirements of a ULS re-supply process. This infrastructure would need to be robust and flexible in order to support visibility and communication at all units.

C. SUMMARY

Marine Corps logistics serves the warfighter, and its processes need to be flexible and sustainable enough to support dispersed and varied combat operations. While the Marine Corps is currently performing logistics without the ULS, the addition of this adaptive technology to the logistician's arsenal will add process flexibility, reduce risk, and help modernize the force. Whether this asset is employed to keep re-supply trucks off improvised explosive device-laden roads, free air assets to perform missions other than delivery, or act as a ship-to-shore connector, this simulation and analysis shows that ULSs are a capability that enable efficient logistics throughput and ultimately increase combat power.

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LIST OF REFERENCES

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